California Energy Commission

CONSULTANT REPORT

Codes and Standards Enhancement – Quality Demonstration Program

Appendices E-G

California Energy Commission

Gavin Newsom, Governor

January 2019 | CEC-500-2019-005-APE-G

APPENDIX E:
GHP Assessment Report

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

Buildings consume 70% of the electricity in the US, 50% of which is used for commercial buildings. Heating, Cooling and ventilation account for more than 35% of the annual primary energy consumption of commercial buildings in California (EIA 2012). Air conditioning is the largest single contributor to peak electrical demand. Rooftop units are usually the largest single connected load in a commercial building, and can account for more than 50% of the on-peak demand from commercial facilities.

California's electric grid is especially stressed during summer periods when electricity generation requirements can be twice as high as other seasons. On the hottest summer days, air conditioning alone accounts for more than 30% of the peak demand on the statewide electric network (EIA 2014, CEC 2006). Similar peaks in electricity demand are not observed in the winter because the majority of heating is achieved with natural gas.

Gas engine heat pumps (GEHPs) are a technology that can eliminate the peak demand by producing the mechanical energy necessary to drive the vapor compression cycle on-site from natural gas. Manufacturers claim the efficiency of a gas engine heat pump is similar to an electric heat pump when losses during electricity generation and transmission are accounted for. Since air conditioning loads are such a singularly large fraction of statewide electricity demand, these systems can significantly reduce a buildings impact on the electric grid.

Project Purpose

The intent of this project was to characterize the performance and energy efficiency of a GEHP installed in the field. The field performance of the GEHP was compared to the manufacturer published performance data. Additionally, to provide a comparison, the measured performance of the GEHP in the field was compared to the predicted performance of an electric heat pump while operating at the same conditions and delivering the same amount of cooling or heating.

Project Results

When providing heating, the monitored GEHPs demonstrated their heat recovery features and were shown to use less source energy than was predicted for a comparable Daikin Electric Heat Pump. However, when providing cooling both monitored GEHPs used more source energy than was predicted for a comparable Daikin Electric Heat Pump.

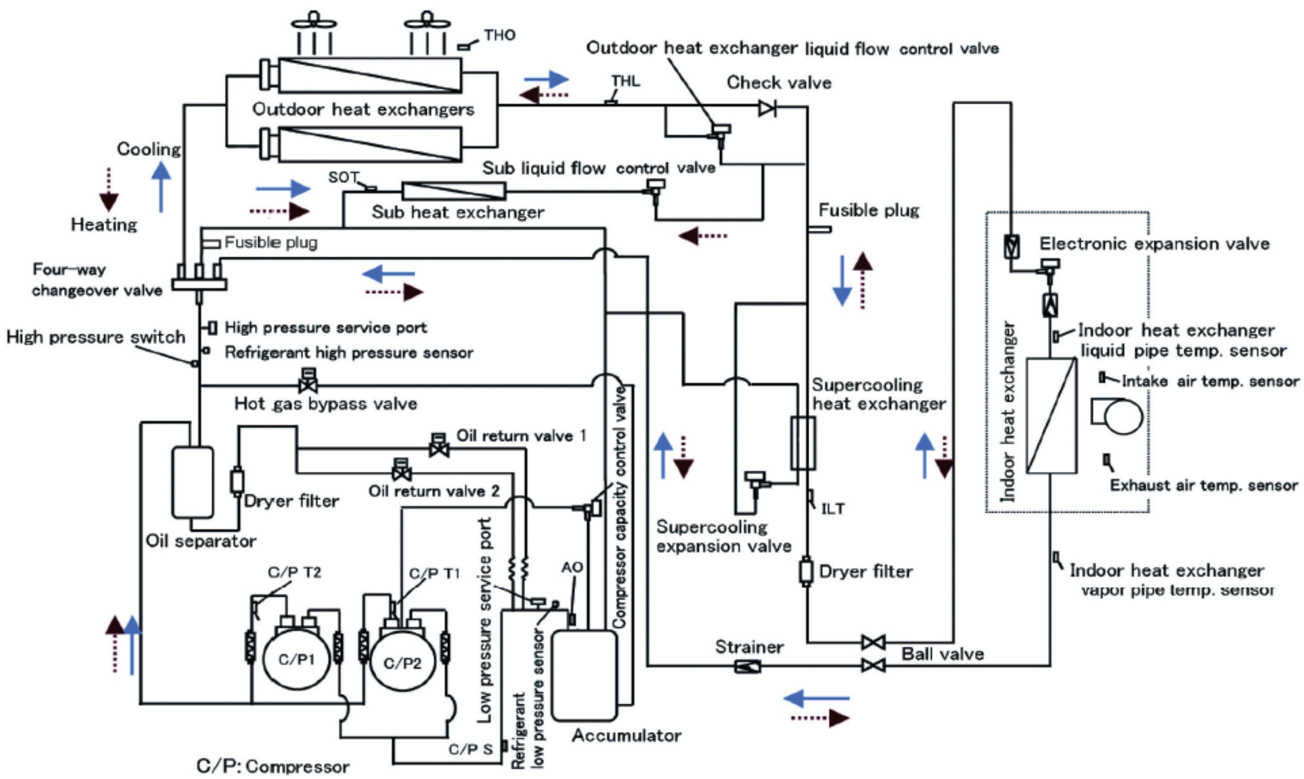
The annual cost of energy to operate GEHP #7 was estimated at $3,268, which is approximately 10% more than the predicted cost to operate a comparable Daikin EHP of $2,977. The annual cost of energy to operate GEHP #22 was estimated at $3,094, which is approximately 50% more than the predicted cost to operate a comparable Daikin EHP of $2,011. Although GEHP #22 was estimated to cost less to operate than GEHP # 7, it provided less cooling and heating of the two GEHPs.

Due to the low rate of CO_2 emissions for electricity produced in California both units were estimated to produce more CO_2 than was predicted for a comparable Daikin EHP. However, if the national average CO_2 emission rate for electricity production was used in the comparison, the CO_2 emissions from the GEHPs would be approximately equal to that predicted for a comparable Daikin EHP. GEHP #22 consistently performed worse than GEHP #7 indicating that it may have been commissioned incorrectly or it is need of maintenance.

TECHNOLOGY OVERVIEW

Monitoring was performed on two NextAire 15-ton multi-zone outdoor heat pumps. This device utilizes a natural gas (or propane) fueled internal combustion engine to drive a standard vapor compression heat pump system. The unit employs multiple heat exchangers to recover heat from both the engine coolant and the exhaust streams. This heat is used to increase the system efficiency and augment performance at low temperatures. A schematic of the system is shown in Figure 1 and the full specifications for this unit can be found in Appendix I.

Figure 1 - GEHP system schematic



The heat recovery is a unique feature of the GEHP equipment and has the potential for increasing system performance by producing power onsite. In this system, heat is directly recovered from engine coolant by passing it through an engine-coolant-to-refrigerant heat exchanger. Heat is also indirectly recovered from the engine exhaust heat, which is linked to the engine coolant loop by an exhaust-gas-to-engine-coolant heat exchanger. There are three modes of heat recovery based on the temperature of the engine coolant as shown in Table 1.

Table 1 – Heat Recovery Modes (Heating mode only)

Engine Coolant Temperature	Operation
< 140°F	The exhaust gas heat is recovered and added to the engine coolant stream. Engine coolant is recirculated and no heat is delivered to the refrigerant heat exchanger. The external radiators are not used.
140°F - 153°F	The exhaust gas heat is recovered and added to the engine coolant stream. Engine coolant is delivered to the refrigerant heat exchanger and used to augment heat pump performance. The external radiators are not used.
> 153°F	The exhaust gas heat is recovered and added to the engine coolant stream. Engine coolant is not delivered to the refrigerant heat exchanger. The external radiators are used to reject all heat to the environment.

MONITORING PLAN

Field Test Site

Field monitoring of the 15-ton NextAire GEHPs took place at a commercial building located in downtown Los Angeles, California. The commercial building has 25 installed 15-ton NextAire GEHPs (Figure 2) and 112 installed Daikin indoor fan coils of various capacities. The indoor fan coils are installed in various configurations; where possible the existing ducts from past installations were reused and in some cases multiple fan coils were stacked (Figure 3) to achieve a larger capacity and allow the total cooling capacity to be staged. Two stacks of three indoor fan coils located in the 7th floor mechanical room were chosen for monitoring. Each stack of three fan coils is connected to a single GEHP.

Figure 2 – A bank of 25 15-ton GEHPs

Figure 3 – Three stacked fan coils

Each of the 25 GEHPs were assigned a number by the facilities manager. The GEHPs monitored were numbered #7 and #22.

Instrumentation

All six indoor fan coils (three from each stack) and the two connected GEHPs were monitored. A combination of continuous monitoring and one-time measurements were used to capture the performance of GEHPs and the connected indoor units.

One-time Measurements

Airflow

Air-flow through the indoor fan coils was measured using a tracer-gas system (Figure 4) that injects a known amount of CO_2 into the airstream and determines the flowrate by measuring the concentration of CO_2 before and after the point of injection. This technique is accurate however the required equipment and materials make continuous monitoring impractical.

Figure 4 – Tracer-gas Air Flow Measurement System

Voltage

The voltage delivered to each piece of equipment was measured using a multi-meter during the initial installation of instrumentation. This measurement, along with the recorded electrical current on each leg, was used to calculate the total power consumption of each piece of equipment.

Continuous Monitoring

In order to capture important performance characteristics including energy use and delivered cooling and heating, instrumentation was installed on both the GEHPs and the Indoor Fan Coils. Two DataTakers (Figure 5) were used to collect the field measurements, one recorded the instrument signals from the sensors installed on the six of the indoor fan coils and the second DataTaker recorded the instrument signals from the sensors installed on the GEHPs. Measurements were logged at one minute intervals and uploaded to a WCEC server by a cellular gateway for a period of one calendar year.

Figure 5 – DataTaker with a cellular modem.

The instrumentation installed on each GEHP and connected fan coils are shown in Table 2.

Table 2 – Instrumentation installed on each GEHP and connected indoor fan coils

Name	Measurement	Sensor	Uncertainty
T_{OA}	Temperature – Outside Air	Vaisala HUMICAP HMP110	± 0.2 °C
RH_{OA}	Relative Humidity – Outside Air	Vaisala HUMICAP HMP110	± 1.1% RH
T_{RA}	Temperature – Return Air	Vaisala HUMICAP HMP110	± 0.2 °C
RH_{RA}	Relative Humidity – Return Air	Vaisala HUMICAP HMP110	± 1.1% RH
T_{SA}	Temperature – Supply Air	Vaisala HUMICAP HMP110	± 0.2 °C
RH_{SA}	Relative Humidity – Supply Air	Vaisala HUMICAP HMP110	± 1.1% RH
ΔP_{SA}	Supply Plenum Pressure	Dwyer 668-1	± 1% FS
CT_{GEHP}	AC Current – GEHP	NK AT1-005-000-SP	± 1% FS
CT_{FC-T}	AC Current – Fan Coil (Top)	NK AT1-005-000-SP	±1% FS
CT_{FC-M}	AC Current – Fan Coil (Middle)	NK AT1-005-000-SP	± 1% FS
CT_{FC-B}	AC Current – Fan Coil (Bottom)	NK AT1-005-000-SP	± 1% FS
V_{NG}	System Natural Gas Consumption	Alicat MW-250SLPM-D	±(0.8% Reading + 0.2% FS)

GEHP Instrumentation

Ambient air conditions: The ambient air dry-bulb temperature and relative humidity (T&RH) were measured using a Vaisala HMP110. The T&RH sensor was installed in a radiation shield.

Power: The electric power consumption of the electric fans on the GEHP was monitored using current transducers. The voltages on each leg were measured as one-time measurements using a multi-meter. Together, the voltages and recorded electrical currents on each leg were used to calculate the total electric power consumption of each piece of equipment.

Natural Gas Fuel Consumption: The natural gas consumed by each GEHP was monitored using an Alicat Whisper Series Mass Flow Meter which was installed at the natural gas inlet connection.

Refrigerant Temperature: The refrigerant temperatures entering and leaving the GEHP were monitored using onboard RTDs that are a standard part of the GEHPs internal diagnostics.

Refrigerant Pressure: The refrigerant pressures entering and leaving the GEHP were monitored using onboard pressure transducers that are a standard part of the GEHPs internal diagnostics.

Indoor Fan Coil Instrumentation

Power: The electric power consumption of each fan coil was monitored using current transducers. The voltages on each leg were measured as one-time measurements using a multi-meter. Together, the voltages and recorded electrical currents on each leg were used to calculate the total electric power consumption of each piece of equipment.

Return Air Conditions: The return T&RH were measured using a Vaisala HMP110 mounted in the mechanical room which serves as a return plenum for all six indoor fan coils.

Supply Air Conditions: The supply T&RH were measured using a Vaisala HMP110 mounted in the supply duct of both stacks.

Duct Pressure: The pressure inside the supply duct was measured using a differential pressure sensor.

Refrigerant Temperature: The refrigerant temperatures entering and leaving the fan coils will be measured using onboard RTDs that are a standard part of the fan coils internal diagnostics.

Figure 6 – Instrumentation (from the left: T&RH sensor, Gas Mass Flow Meter, RTD, Current Transducer, differential Pressure Transmitter)

Calculations

Data was collected for the purpose of calculating the electric power consumption, natural gas consumption and delivered capacity of the system at each minute for the duration of the monitoring. Since the system is powered from a mixed energy source (electric and natural gas) all power measurements and calculations were converted to source energy. According to the EPA [2] the source-site ratio for electricity is 3.14 and for natural gas it is 1.05. Additional performance metrics that were calculated from the collected data include the Energy Input Ratio (EIR), Coefficient of Performance (COP) and Part Load Ratio (PLR).

Power Consumption

The electric power consumption of the entire system was calculated using Equation 1.

$$P_{Electric} = \left(V_{GEHP} \cdot CT_{GEHP} + V_{FC} \cdot \left(CT_{FC_{Top}} + CT_{FC_{Middle}} + CT_{FC_{Bottom}}\right)\right)/1000$$

Equation 1

Where $P_{Electric}$ is the electric power consumption (kW), V_{GEHP} is the A/C voltage (V_{RMS}) measured at the GEHP, CT_{GEHP} is the GEHP electric current (A_{RMS}) measured at the GEHP, V_{FC} is the voltage (V_{RMS}) measured at the fan coil, and $CT_{FC_{Top}}$, $CT_{FC_{Middle}}$ and $CT_{FC_{Bottom}}$ are the electric currents (A_{RMS}) measured at the top, middle and bottom fan coil respectively.

The power consumption in natural gas was calculated using Equation 2.

$$P_{NG} = \dot{V}_{NG} \cdot \rho_{NG} \cdot u_{NG}$$

Equation 2

Where P_{NG} is the is power consumption in natural gas (kW), $\dot{V}_{NG}$ is the volume flow rate of natural gas (m^3/s) into the GEHP, ρ_{NG} is the density of natural gas at STP (0.712 kg/m^3) and u_{NG} is the energy density of natural gas (53600 kJ/kg).

The total system source power consumption was calculated using Equation 3.

$$P_{Source} = P_{Electric} \cdot 3.14 + P_{NG} \cdot 1.05$$

Equation 3

Where P_{Source} is the source power consumption (kW) of the system, $P_{Electric}$ is the electric power consumption (kW) and P_{NG} is the power consumption in natural gas.

Delivered Capacity

The total delivered capacity of the system was calculated using an energy balance performed on the air flowing through the indoor coils shown in Equation 4.

$$H = \dot{V}_{air} \cdot \rho_{air} \cdot (h_{RA} - h_{SA})$$

Equation 4

Where H is the delivered capacity (kW), $\dot{V}_{air}$is the volume flow rate of air (kg/s), ρ_{air} is the density of air (1.225 kg/m^3), h_{RA} is the return air specific enthalpy (kJ/kg) and h_{SA} is the supply air specific enthalpy (kJ/kg). As shown in Equation 4, a negative capacity indicates that the system is delivering heating and a positive capacity indicates that the system is delivering cooling. The return and supply air specific enthalpies were calculated from the dry-bulb temperature and relative humidity using empirical equations published in the ASHRAE Fundamentals handbook [1].

Energy Input Ratio

The Energy Input Ratio (EIR) is the ratio of the power input to the system to the capacity delivered by the system. Source power was used as the power input to the system as shown in Equation 5.

$$EIR = \frac{P_{Source}}{H}$$

Equation 5

Coefficient of Performance

The Coefficient of Performance (COP) is the ratio of the capacity delivered by the system to the power input to the system, thus it is the inverse of the EIR as shown in Equation 6. The COP is a more widely used metric for characterizing the efficiency of a vapor compression system.

$$COP = \frac{H}{P_{Source}}$$

Equation 6

Part Load Ratio

The Part Load Ratio (PLR) described in Equation 7 is the ratio of the total capacity required by the indoor coils to the total capacity available at the heat pump.

$$PLR = \frac{H_{FC}^{Demand}}{H_{HP}^{Avaliable}}$$

Equation 7

Where PLR is the part load ratio, H_{FC}^{Demand} is the total capacity required by the fan coils and $H_{HP}^{Avaliable}$ is the total capacity available at the heat pump.

Operating Cost

The cost for electricity used in calculations was $0.16 per kWh [6]. The cost of natural gas used in calculations was $1.12 per therm [5]. Converting therms into kWh of natural gas reveals that the cost of natural gas is $0.038 per kWh.

CO_2 Emissions

Another important performance metric of GEHPs is the CO_2 emissions based on their gas and electrical consumption. According to PG&E [3] 0.391 pounds of CO_2 is released into the atmosphere for each kWh of electricity used and 11.7 pounds of CO_2 is released into the atmosphere for every combusted therm of natural gas. Converting therms into kWh of natural gas reveals that 0.399 pounds of CO_2 is released into the atmosphere for each kWh of natural gas combusted.

Comparisons

Since the GEHPs were installed at the field site prior to the beginning of the demonstration it was not possible to collect a baseline for comparison. Instead, the performance of an electric heat pump (EHP) was estimated using performance data published by the manufacturer. Performance for Daikin VRV III electric heat pumps were used for the comparison. These performance curves were normalized by rated capacity which enabled the modeling of an electric heat pump with a rated capacity equivalent to the GEHPs installed at the demonstration site. Equation 7 through Equation 12 were used to characterize the performance of the EHP.

$$H_{Cooling}^{Modifier} = A + B \cdot T_{wb}^{RA} + C \cdot (T_{wb}^{RA})^2 + B \cdot T_{db}^{OA} + C \cdot (T_{db}^{OA})^2 + D \cdot T_{wb}^{RA} \cdot T_{db}^{OA}$$

Equation 8

$$EIR_{Cooling}^{T\ Modifier} = A + B \cdot T_{wb}^{RA} + C \cdot (T_{wb}^{RA})^2 + B \cdot T_{db}^{OA} + C \cdot (T_{db}^{OA})^2 + D \cdot T_{wb}^{RA} \cdot T_{db}^{OA}$$

Equation 9

$$EIR_{Cooling}^{PLR\ Modifier} = A + B \cdot PLR + C \cdot PLR^2$$

Equation 10

Where $H_{Cooling}^{Modifier}$ is the cooling capacity of the EHP, $EIR_{Cooling}^{T\ Modifier}$ is the cooling EIR modifier due to temperature, $EIR_{Cooling}^{PLR\ Modifier}$ is the cooling EIR modifier due to PLR, T_{wb}^{RA} is the return air wet-bulb temperature, T_{db}^{OA} is the outdoor air dry-bulb temperature and PLR is the part load ratio.

$$H_{Heating}^{Modifier} = A + B \cdot T_{db}^{RA} + C \cdot (T_{db}^{RA})^2 + B \cdot T_{wb}^{OA} + C \cdot (T_{wb}^{OA})^2 + D \cdot T_{db}^{RA} \cdot T_{wb}^{OA}$$

Equation 11

$$EIR_{Heating}^{T\ Modifier} = A + B \cdot T_{db}^{RA} + C \cdot (T_{db}^{RA})^2 + B \cdot T_{wb}^{OA} + C \cdot (T_{wb}^{OA})^2 + D \cdot T_{db}^{RA} \cdot T_{wb}^{OA}$$

Equation 12

$$EIR_{Heating}^{PLR\ Modifier} = A + B \cdot PLR + C \cdot PLR^2$$

Equation 13

Where $H_{Heating}^{Modifier}$ is the heating capacity of the EHP, $EIR_{Heating}^{T\ Modifier}$ is the heating EIR modifier due to temperature, $EIR_{Heating}^{PLR\ Modifier}$ is the cooling EIR modifier due to PLR, T_{db}^{RA} is the return air dry-bulb temperature, T_{wb}^{OA} is the outdoor air wet-bulb temperature and PLR is the part load ratio.

The modifiers output from Equation 7 through Equation 12 were used with Equation 13 through Equation 16 to determine the total capacity and EIR of the EHP.

$$H_{Cooling} = H_{Cooling}^{Rated} \cdot H_{Cooling}^{Modifier}$$

Equation 14

$$EIR_{Cooling} = EIR_{Cooling}^{Rated} \cdot T_{Cooling}^{EIR\ Modifier} \cdot PLR_{Cooling}^{EIR\ Modifier}$$

Equation 15

$$H_{Heating} = H_{Heating}^{Rated} \cdot H_{Cooling}^{Modifier}$$

Equation 16

$$EIR_{Heating} = EIR_{Heating}^{Rated} \cdot T_{Heating}^{EIR\ Modifier} \cdot PLR_{Heating}^{EIR\ Modifier}$$

Equation 17

Where $H_{Cooling}$ is the total cooling capacity of the EHP, $H_{Cooling}^{Rated}$ is the total capacity of the EHP at rated cooling conditions, $EIR_{Cooling}$ is the cooling EIR of the EHP, $EIR_{Cooling}^{Rated}$ is the EIR of the EHP at rated cooling conditions, $H_{Heating}$ is the total heating capacity of the EHP, $H_{Heating}^{Rated}$ is the total capacity of the EHP at rated heating conditions, $EIR_{Heating}$ is the heating EIR of the EHP and $EIR_{Heating}^{Rated}$ is the EIR of the EHP at rated heating conditions.

Using the six performance curves the performance of the EHP was predicted at every recorded minute of the field data. Additionally, similar curves were generated based on the manufacturers data for the performance of the GEHP so the field performance of the GEHP could be compared to the performance claimed by the manufacturer.

RESULTS AND ANALYSIS

Airflow

The results from the tracer gas measurements are shown in Table 3. The three fan coils in each stack were not measured individually because they supplied air to a common duct and were wired to one thermostat, thus turning on and off together. Due to their configuration, powering the fan coils individually would have resulted in backflow through the other fan coils thus yielding an inaccurate result.

Table 3 – Measured fan coil air flow rates

Connected GEHP	Total Fan Coil Airflow (CFM)
GEHP # 7	7771
GEHP # 22	8466

The airflow through GEHP #7 was less than the airflow through GEHP # 22 however the static pressure measured inside each supply duct was 149 Pa with a measured standard deviation during fan operation of 1 Pa. Since both ducts are operating at the same pressure the duct that GEHP #22 supplied must have less flow resistance in it than the duct that GEHP #7 supplied, thus allowing more flow at the same pressure.

Cooling

The air temperatures recorded on June 21st, 2016 are shown in Figure 7. These measurements were used in the energy balance calculations to determine the cooling delivered by GEHP #7 and GEHP #22 on that day. June 21st, 2016 was chosen because it was a particularly hot day at the field site and the building was occupied during normal business hours thus yielding an excellent snapshot of the cooling performance of the GEHPs.

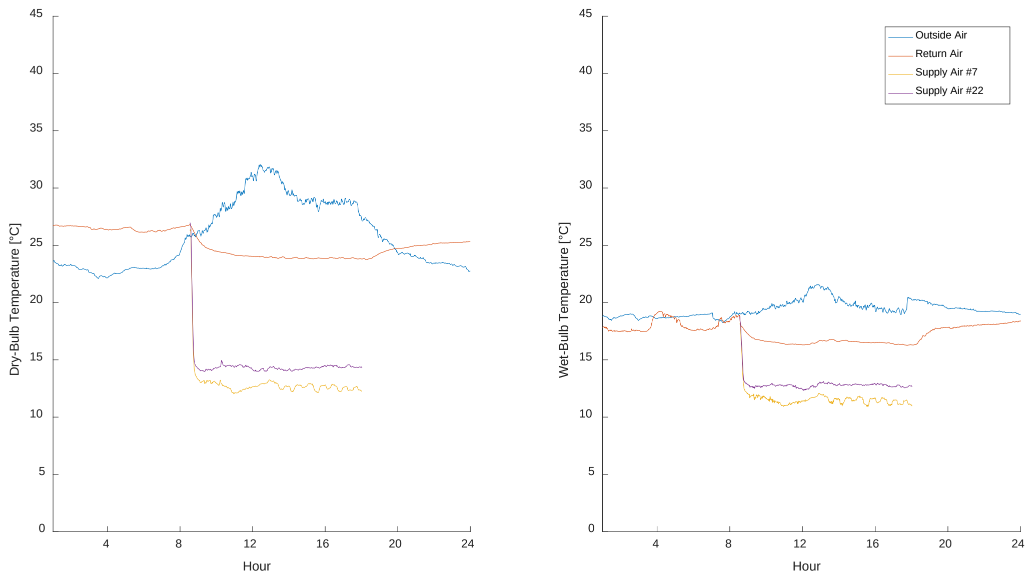


Figure 7 – Recorded air temperatures. June 21, 2016.

The resulting calculated cooling capacity and recorded natural gas and electricity consumption for GEHP #7 and GEHP #22 are shown in Figure 8 and Figure 9 respectively.

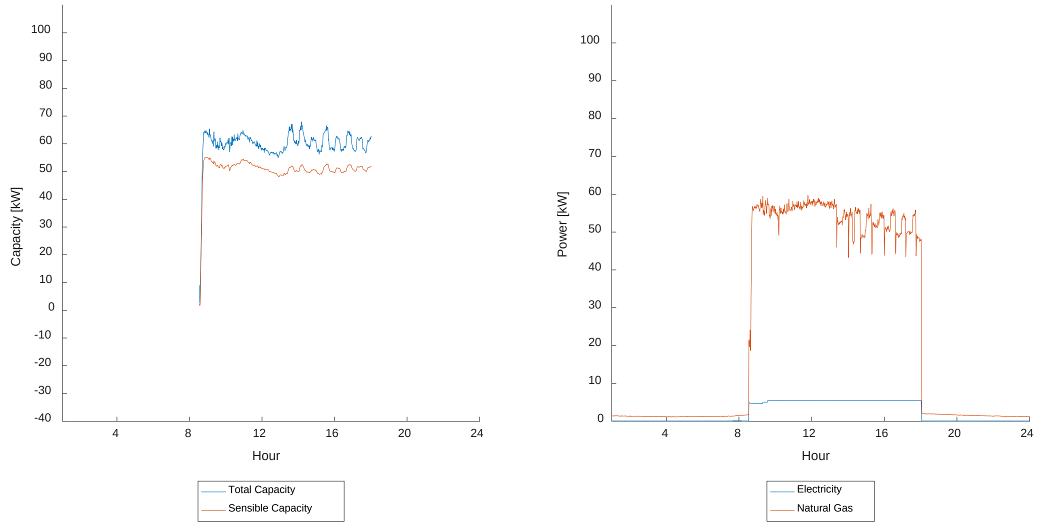


Figure 8 – Calculated cooling capacity and measured site power consumption for GEHP #7. June 21, 2016.

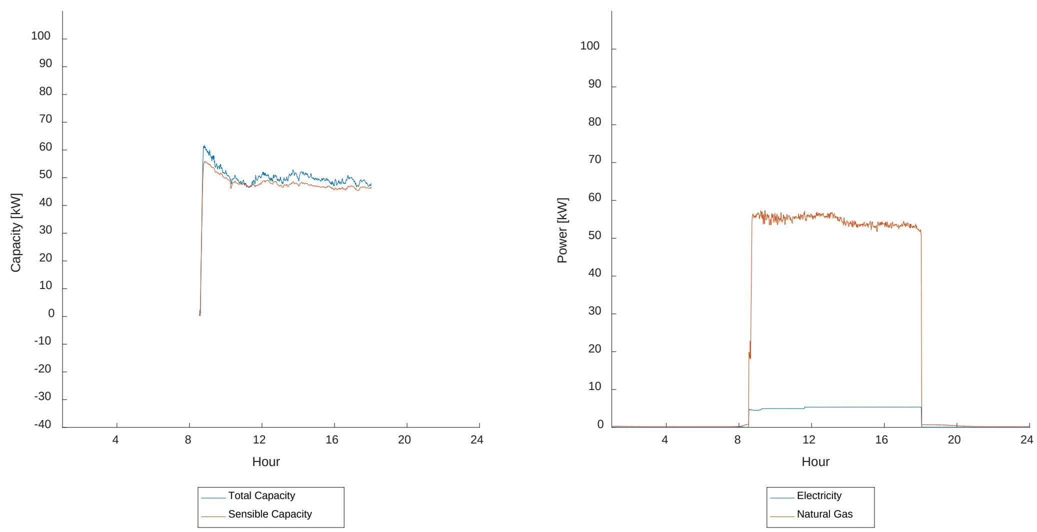


Figure 9 – Calculated cooling capacity and measured site power consumption for GEHP #22. June 21, 2016.

The supply air temperature produced by GEHP #22 was not as cold as the supply air produced by GEHP #7. Additionally, throughout the day, GEHP #7 does more latent cooling than GEHP #22 which does almost no latent cooling. This performance is supported by the difference in airflow across the fan coils attached to GEHP #7 and GEHP #22; lower airflows result in longer residence time inside the fan coil allowing more cooling and dehumidification to take place.

The source power consumption of GEHP #7 and GEHP #22 are compared in Figure 10 to the source power consumption predicted by performance curves for a comparable Daikin electric heat pump as well as the GEHP. Both performance curves were generated using data provided by the manufacturer.

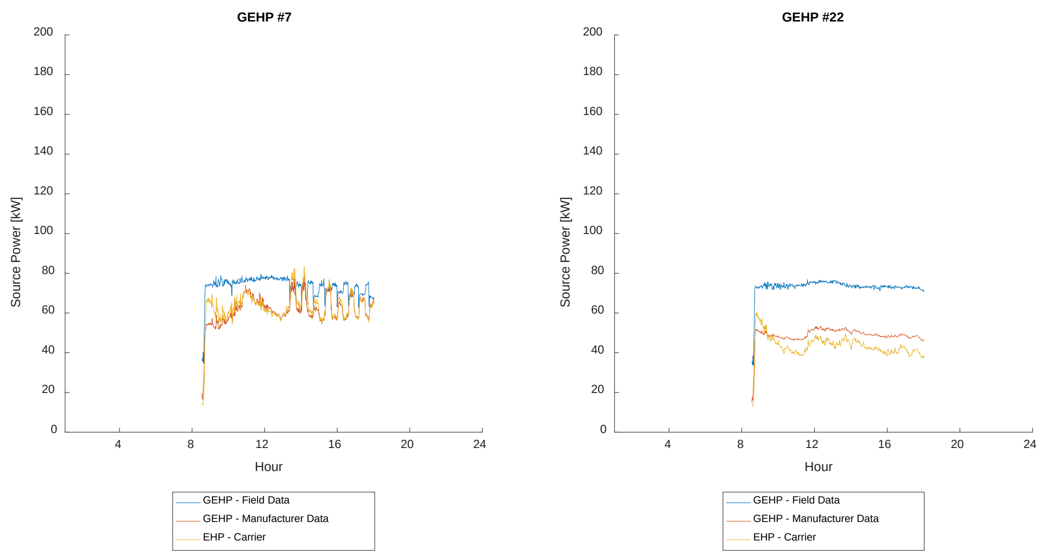


Figure 10 – Source power consumption of GEHP #7 and GEHP #22 and predicted source power consumption based on manufacturer data for the GEHP and a comparable Daikin electric heat pump. June 21, 2016.

The GEHP curve and the EHP curve predict source power consumptions that are very similar. Both GEHP #7 and GEHP #22 consistently consume more source power than predicted. The difference between the field performance and the predicted performance is more pronounced for GEHP #22.

The source COPs of GEHP #7 and GEHP #22 are compared in Figure 11 to the source COPs predicted by performance curves for a comparable Daikin electric heat pump as well as the GEHP.

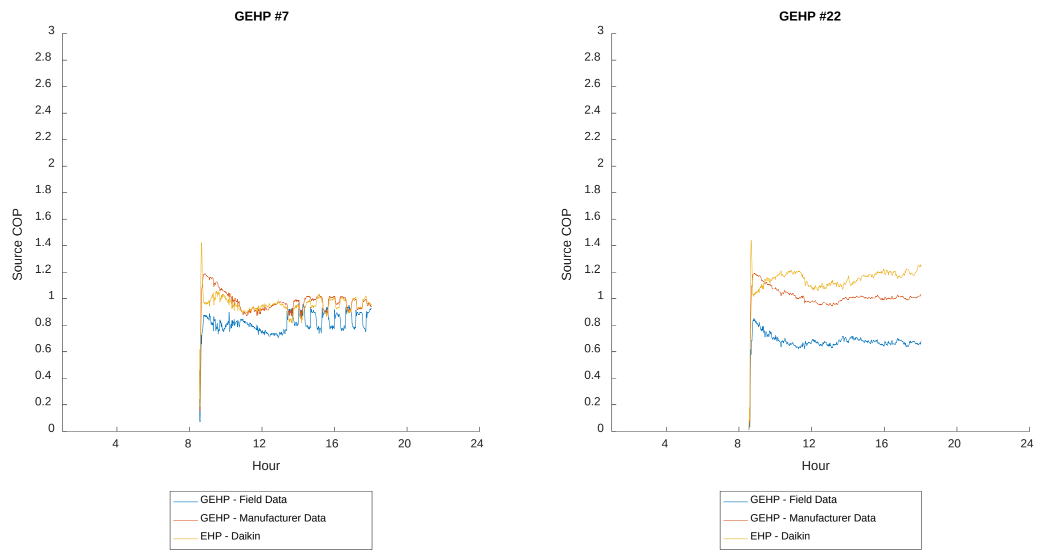


Figure 11 - Source COP of GEHP #7 and GEHP #22 and predicted source COP based on manufacturer data for the GEHP and a comparable Daikin electric heat pump. June 21, 2016.

Since the delivered cooling of each GEHP measured in the field was used as an input for predicting the source power consumption of the EHP and GEHP the resulting source COPs mirror the source power consumption. Thus, the two performance curves predict similar COPs while the GEHPs in the field under-perform.

Heating

The air temperatures recorded on February 6th, 2016 are shown in Figure 12. These measurements were used in the energy balance calculations to determine the heating delivered by GEHP #7 and GEHP #22 on that day. February 6th, 2016 was chosen because it was a particularly cold day at the field site and the building was occupied during normal business hours thus yielding an excellent snapshot of the heating performance of the GEHPs.

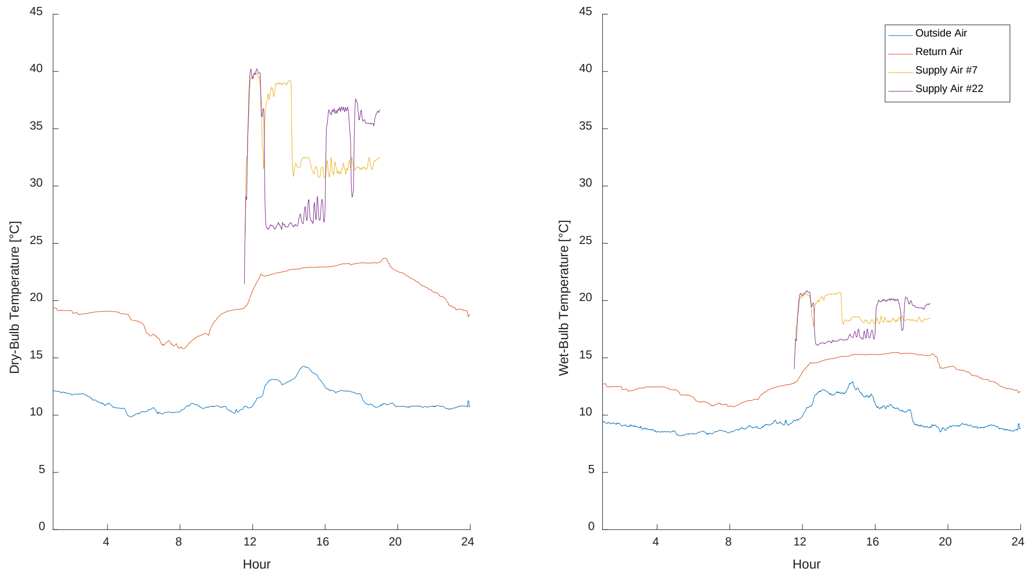


Figure 12 - Recorded air temperatures. February 6, 2016.

The resulting calculated heating capacity and recorded natural gas and electricity consumption for GEHP #7 and GEHP #22 are shown in Figure 13 and Figure 14 respectively.

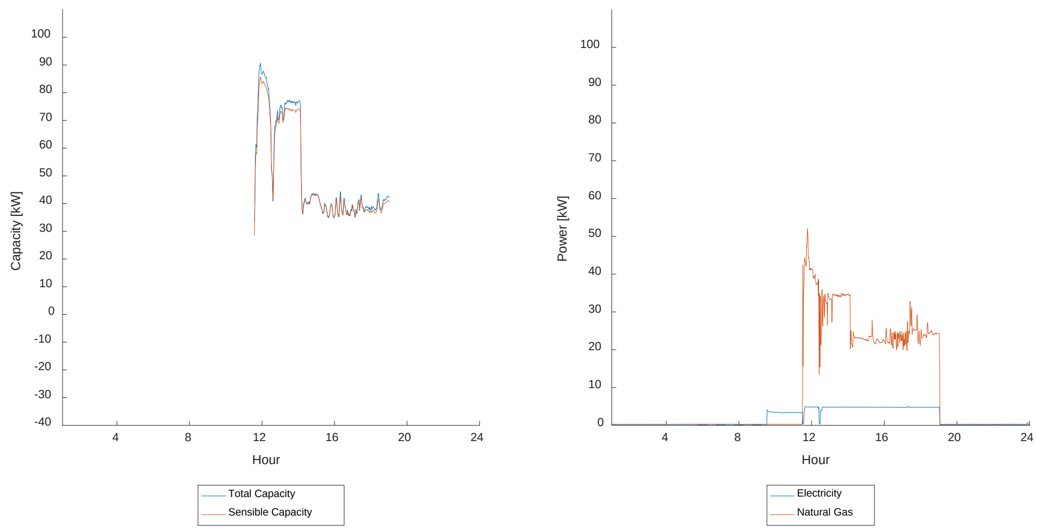


Figure 13 - Calculated heating capacity and measured site power consumption for GEHP #7. February 6, 2016.

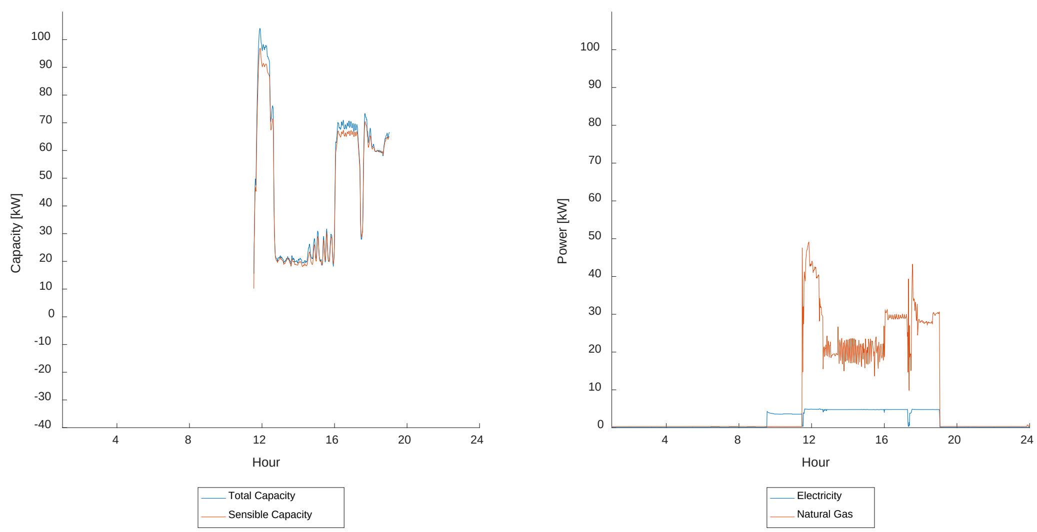


Figure 14 - Calculated heating capacity and measured site power consumption for GEHP #22. February 6, 2016.

Both GEHP #7 and #22 demonstrate similar heating capacities, however they are seen to ramp up and down at different times of the day.

The source power consumption of GEHP #7 and GEHP #22 are compared in Figure 10 to the source power consumption predicted by performance curves for a comparable Daikin electric heat pump as well as the GEHP. Both performance curves were generated using data provided by the manufacturer.

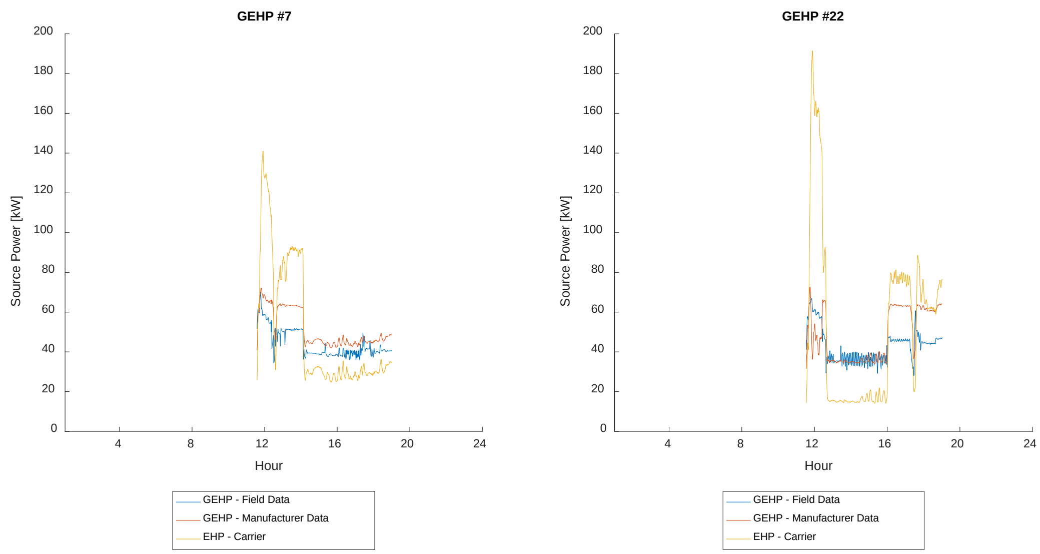


Figure 15 - Source power consumption of GEHP #7 and GEHP #22 and predicted source power consumption based on manufacturer data for the GEHP and a comparable Daikin electric heat pump. February 6, 2016.

The GEHP performance curves predict source power consumptions that are similar to the measured field performance of the GEHPs. In the case of heating, the GEHP performance curves and the EHP performance curves do not predict similar source power consumption. The heat recovery feature of the GEHPs gives them an advantage while heating that they do not have while cooling. As a result the GEHPs are predicted to consume less source power than the EHP.

The source COPs of GEHP #7 and GEHP #22 are compared in Figure 16 to the source COPs predicted by performance curves for a comparable Daikin electric heat pump as well as the GEHP.

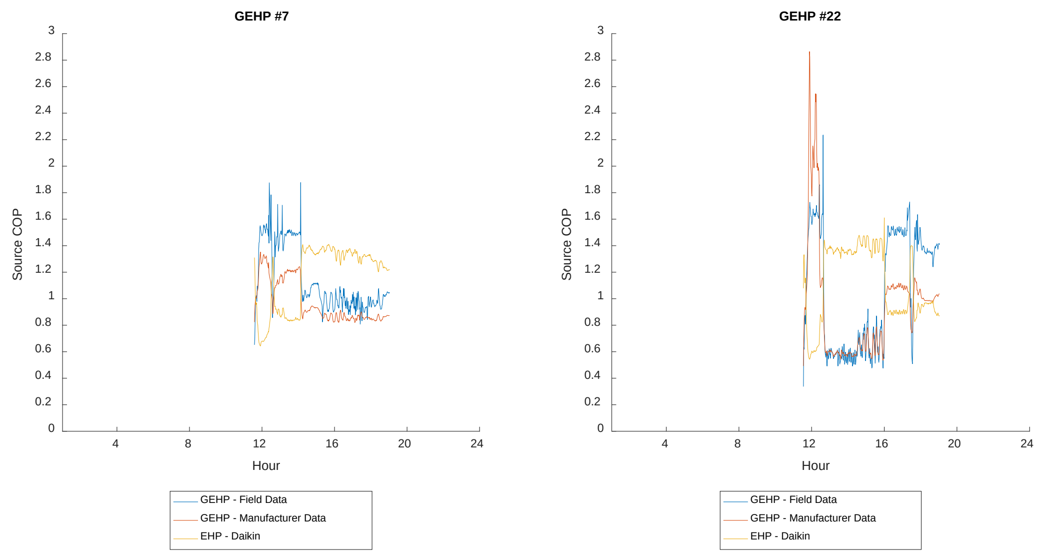


Figure 16 - Source COP of GEHP #7 and GEHP #22 and predicted source COP based on manufacturer data for the GEHP and a comparable Daikin electric heat pump. February 6, 2016.

Since the delivered heating of each GEHP measured in the field was used as an input for predicting the source power consumption of the EHP and GEHP the resulting source COPs mirror the source power consumption. Thus, both the field data from the GEHP and the performance curves for the GEHP show that the GEHPs have a higher COP than is predicted for the comparable Daikin EHP.

Energy Cost

The cost of energy needed to operate each GEHP was calculated for each day of data that was collected. The predicted cost of energy to operate the Daikin EHP was calculated as well and is compared to the field data in Figure 17.

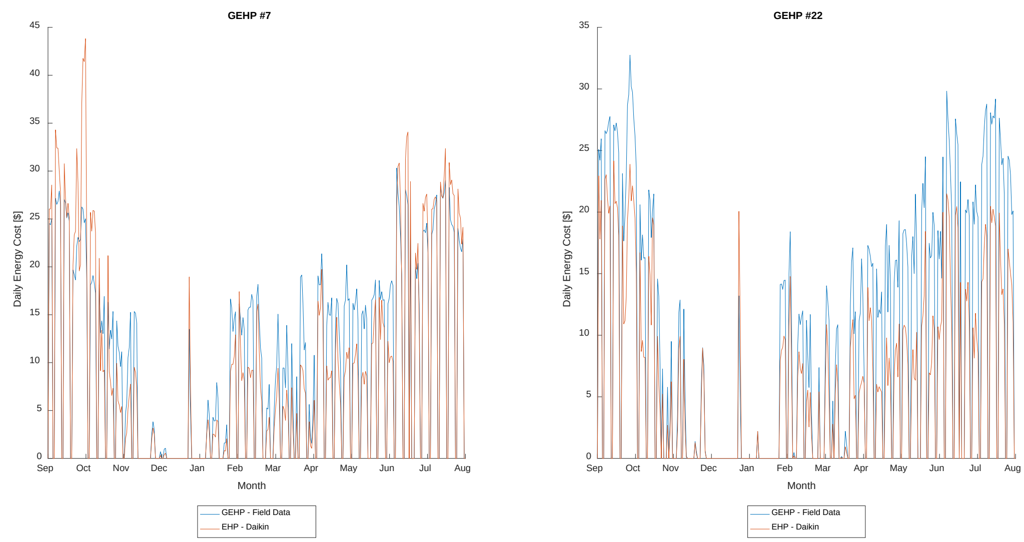


Figure 17 – Estimated energy cost of operating GEHP #7 and GEHP #22 compared to the predicted energy cost of operating a comparable electric heat pump.

The plots in Figure 17 are not continuous because the building was frequently unoccupied during which times, the GEHPs did not operate. The estimated cost to operate GEHP #7 is comparable to the predicted cost to operate the EHP, especially in the winter when the GEHP can take advantage of its heat recovery features and often is estimated to cost less to operate than is predicted for the Daikin EHP. GEHP #22, however, is consistently estimated to cost more to operate than predicted for the Daikin EHP. These results indicate that GEHP #22 may be under-performing due to improper commissioning or needed maintenance. The total estimated and predicted energy costs are shown in Table 4.

Table 4 – Estimated Energy Cost

	GEHP - Field Data	***Predicted Daikin EHP***
GEHP # 7	$3,268	$2,977
GEHP # 22	$3,094	$2,011

CO_2 Emissions

The CO_2 emissions resulting from the operation of each GEHP was calculated for each day of data that was collected. The predicted CO_2 emissions resulting from the operation of a Daikin EHP was calculated as well and is compared to the field data in Figure 18.

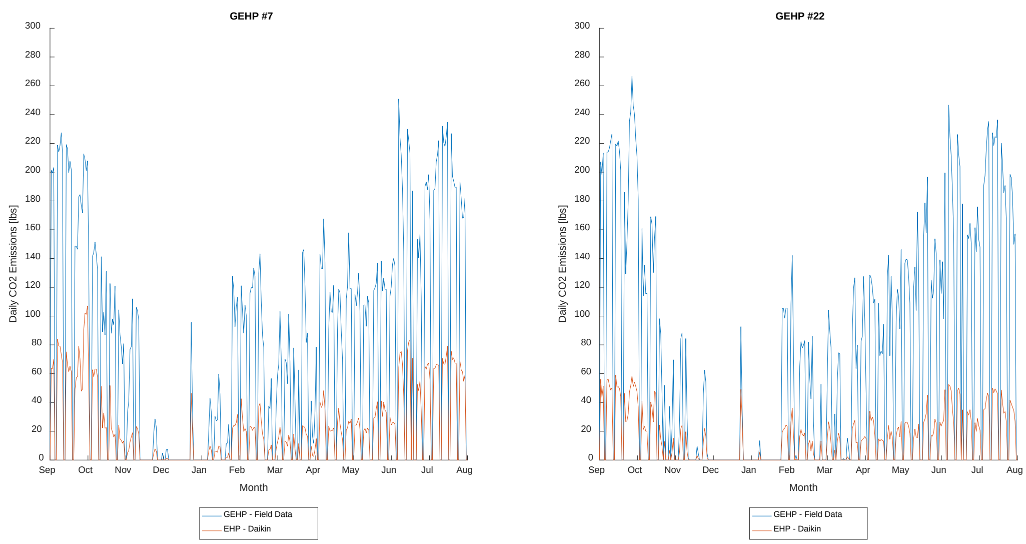


Figure 18 – Estimated CO_2 emissions of GEHP #7 and GEHP #22 compared to the predicted CO_2 emissions of a comparable Daikin electric heat pump.

The GEHPs are estimated to produce more CO_2 emissions than is predicted for a comparable Daikin EHP. The total estimated and predicted CO_2 emissions are shown in Table 4.

Table 5 – Estimated CO_2 emissions

	GEHP - Field Data	Predicted Daikin EHP
GEHP # 7	24,921 lb	7,275 lb
GEHP # 22	23,659 lb	4,914 lb

However, according to PG&E, the CO_2 emission rate for electricity produced by Californian utilities is approximately one third the national average [4]. Thus, the GEHPs should produce fewer CO_2 emissions than a comparable EHP in approximately half of the United States.

CONCLUSION

When providing heating, the monitored GEHPs demonstrated their heat recovery features and were shown to use less source energy than was predicted for a comparable Daikin Electric Heat Pump. However, when providing cooling both monitored GEHPs used more source energy than was predicted for a comparable Daikin Electric Heat Pump.

The annual cost of energy to operate GEHP #7 was estimated at $3,268, which is approximately 10% more than the predicted cost to operate a comparable Daikin EHP of $2,977. The annual cost of energy to operate GEHP #22 was estimated at $3,094, which is approximately 50% more than the predicted cost to operate a comparable Daikin EHP of $2,011. Although GEHP #22 was estimated to cost less to operate than GEHP # 7, it provided less cooling and heating of the two GEHPs.

Due to the low rate of CO_2 emissions for electricity produced in California both units were estimated to produce more CO_2 than was predicted for a comparable Daikin EHP. However, if the national average CO_2 emission rate for electricity production was used in the comparison, the CO_2 emissions from the GEHPs would be approximately equal to that predicted for a comparable Daikin EHP.

GEHP #22 consistently performed worse than GEHP #7 indicating that it may have been commissioned incorrectly or it is need of maintenance.

References

[1] ASHRAE Fundamentals handbook (2005), P6.2 equation 5 and 6, P6.8 equation 22 and 24 P6.9 equation 32

[2] Environmental Protection Agency, Energy Star Portfolio Manager Technical Reference Source Energy, July 2013

[3] PG&E, Greenhouse Gas Emission Factors, PG&E 2013

[4]PG&E , PG&E Cuts Carbon Emissions with Clean Energy, January 30, 2015

[5] U.S. Energy Information Administration, Natural Gas Prices, 2014

[6] U.S. Energy Information Administration, Average Price of Electricity to Ultimate Customers
by End-Use Sector, 2014

Appendix I – NEXTAIRE Technical Specifications

NEXTAIRE™
GAS-FIRED HEAT PUMPS

TECHNICAL SPECIFICATIONS

15-TON MULTI-ZONE OUTDOOR HEAT PUMP

MODEL – AXGP180D1NHS

		UNIT OF MEASURE	VALUE OR DESCRIPTION
Capacity	Rated cooling capacity	BTU/h	180,000
	Rated heating capacity	BTU/h	205,000
External Dimensions	Height	Inch	82.7
	Width	Inch	83.5
	Depth	Inch	39.7
Electric Characteristics	Power supply	Volts	Single-phase 208 or 230
	Starting current (maximum)	Amps	20
	Power consumption	kW	Cooling 1.23
	Power consumption	kW	Heating 1.29
	Operating current	Amps	MCA 11.5
	Operating current	Amps	MOP 20
Engine	Type		Water-cooled straight 4-cycle OHV
	Displacement	Liter	2.237
	Rated output	Hp	23.75
	Starting system		AC/DC conversion DC starter
	Speed range	rpm	Min 800
	Speed range	rpm	Max 1,825
	Lubricant type		AISIN Gas Engine Oil L-10,000G
	Lubricant amount	Liter	40
	Exhaust port position		Top
Engine Coolant	Type		AISIN Coolant S
	Amount	Liter	23
	Concentration	Vol %	50
	Freezing temperature	°F	-4
	Pump type		DC brushless pump
	Pump motor output	Hp	1/6
Compressor	Number of units		4 - Scroll
	Displacement	Inch ^{3}/rev	3.17 x 4
	Speed range	rpm	Cooling 1,480 - 2,960
	Speed range	rpm	Heating 1,572 - 2,960
	Specified refrigerant oil		AISIN NL 10
	Amount of refrigerant oil	Liter	5
	Power transmission system		2 Poly V-belts

HEAT. COOL. SAVE.

NEXTAIRE™
GAS-FIRED HEAT PUMPS

15-TON MULTI-ZONE OUTDOOR HEAT PUMP

MODEL – AXGP180D1NHS

		UNIT OF MEASURE	VALUE OR DESCRIPTION	
Refrigerant	Type		R410A	
	Amount	lbs	25.4	
Heat Exchanger	Outdoor heat exchanger		Slit Fin	
	Exhaust air heat exchanger		Multi-tube heat exchanger	
	Engine radiator		Louver fin	
Fan	Type		Propeller fan (x 3)	
	Rated air volume	cfm	15,362	
	Motor type		Brushless DC motor (8P)	
	Motor rated output	Hp	1/3 x 3	
Piping Diameter/Size	Refrigerant liquid line	Inch	5/8OD	
	Refrigerant vapor line	Inch	1 1/8OD	
	Fuel gas connection	NPT	3/4	
	Exhaust port	Inch	3 1/8	
	Exhaust air drain pipe	Inch	5/8	
Permissible Trunk Piping Length	Equivalent length/Actual length	Feet	623/541	
Permissible Height Between IUs & OUs	Outdoor unit installed above indoor units	Feet	164	
	Outdoor unit installed below indoor units	Feet	131	
Permissible Vertical Distance Among IUs		Feet	49	
Connectable Indoor Units	Number of units		1 - 33	
	Total capacity	BTU/h	90,000 – 234,000	
Additional Specifications	Air inlet port		Front/Back	
	Air outlet port		Top	
	Exhaust heat recovery system		Plate heat exchanger (Refrigerant heating)	
	Defrosting system		Hot gas bypass system	
	Noise	dB	56 - 58	
	Weight	lbs	2,006	
	Fuel gas consumption	BTU/h	Cooling @ 95°F	189,000
	Fuel gas consumption	BTU/h	Heating @ 47°F	165,000

NOTE 1) Capacity and electric characteristics values were measured in accordance with AISIN standard under ANSI/UL 1955, CAN/CSA C22.2 236-05 condition.

NOTE 2) The noise level is measured in an anechoic room conforming to JIS standard. Actual noise level may be louder than measured value due to ambient noise and/or reverberation.

APPENDIX F:
CWPB Assessment Report

EXECUTIVE SUMMARY

Introduction

California businesses, such as hotels, restaurants and athletic facilities, consume water, electricity, and gas in order to provide customers with clean laundry essential to operations. Reducing the consumption of these resources will help the state meet its goals for energy efficiency and greenhouse gas reduction, alleviate pressure on the state's water resources, and reduce costs for California business owners.

The Polymer Bead Laundry (PBL) system is a commercial laundry system designed to reduce water and natural gas consumption without reducing cleaning performance. This new laundry system uses polymer beads to increase mechanical action and absorb soiling agents. The cleaning action achieved by the polymer beads requires less water and operates effectively at a lower temperature than a traditional clothes washing machine. Significant natural gas savings can be achieved by using the PBL technology since the water used by the system does not have to be heated.

Project Purpose

The purpose of this project is to study the potential resource and economic savings that can be achieved by the replacement of a typical commercial washing machine with the PBL washing system. The goal of the research is to produce a representative comparison between current laundry technology and the new system; as well as provide useful data for evaluating the feasibility of the technology and for identifying barriers to its entry into the market.

An Industrial Washer Extractor was chosen as the baseline technology used in the comparison analysis to the PBL system. The capacity of the baseline system is 60 pounds of laundry; the capacity of the PBL system is 65 pounds of laundry.

Project Results

The polymer bead technology successfully demonstrated its effectiveness in significant gas and water savings relative to the baseline system, while only using slightly more electricity. An in-depth energy analysis shows that the net source energy use was reduced by approximately 63% and greenhouse gas emissions were reduced by approximately 90%.

Although the PBL system reduced operating costs, the capital investment was much higher than the washing machine using traditional hot water and detergent. An economic analysis showed that the PBL system would have to process at least 1,100 pounds of laundry per day to achieve the same net cost as the baseline system. This amounts to approximately 17 hours of operation per day. This was identified as a potential barrier to widespread adoption of the polymer bead laundry washing technology.

Project Benefits

This project provides a side-by-side comparison of the PBL polymer bead laundry system and a typical commercial laundry washing machine. The data analysis should be used by the state, the utilities and the manufacturer, to determine the next steps forward for the PBL technology.

The field evaluation confirmed the significant energy and water saving capabilities of the PBL technology. However, the cost analysis revealed that a reduction in the required capital investment for the technology needs to occur for it to be an economically feasible alternative for consumers in California.

Chapter 1: Technology Overview

Technology Description

This project investigates the savings potential of the Polymer Bead Laundry (PBL) system (Figure 1), a laundry washing machine that is expected to reduce water and natural gas consumption. The PBL system uses approximately 1.5 million pebble-sized polymer beads that aid in the cleaning process and reduces water and gas use compared to a typical commercial washing machine.

Figure 19: PBL Washing System

The polymer beads increase mechanical action and have absorptive properties that allow them to remove stains, dyes, and soils from fabrics. The polymer beads are separated from the laundry load during an extraction cycle and are retained for repeated uses. The absorptive properties of the polymer beads persist for hundreds of washes before the cleaning performance degrades to a point that replacement of the beads is necessary. Following replacement, the used polymer beads are recycled at the manufacturers facilities. Occasionally, a few beads will not be fully extracted during the extraction cycle and remain with the laundry load; however, it is a negligible amount.

The cleaning action of the polymer beads requires less water and is effective at water temperatures as low as ambient. Thus, in addition to saving water, the energy cost associated with heating the water is eliminated, resulting in substantial natural gas savings.

Federal and State Regulations

The PBL system is subject to regulations imposed by California's 2014 Appliance Efficiency Standards as well as the Code of Federal Regulations.

Testing

The testing of a commercial clothes washing machine is federally regulated. California's 2014 Appliance Efficiency Regulations references these regulations in the Code of Federal Regulations (10 CFR Part 430, Subpart B, Appendix J1). Although the focus of these regulations is on residential laundry washing machines; the federal and state regulations specify that these regulations apply to commercial laundry washing machines as well.

Efficiency Standards

The efficiency standards for commercial laundry washing machines are federally regulated. These efficiency standards are tabulated in the Code of Federal Regulations (10 CFR 431.156) and California's 2014 Appliance Efficiency Regulations. The PBL system is classified as a front-loading commercial washer and is therefore required to have a minimum modified energy factor of $2\,ft^3/kWh/wash$ and a maximum water factor of $5.5\,gal/ft^3/wash$.

The equations for calculating the modified energy factor as well as the water factor are shown in Equation 1 and Equation 2.

Equation 18: Modified Energy Factor

$$Modified\ Energy\ Factor = \frac{C}{G+E}$$

Equation 19: Water Factor

$$Water\ Factor = \frac{W}{C}$$

Where:

$C = Volume\ of\ the\ wash\ drum\ [ft^3]$

$G = Mean\ natural\ gas\ consumption\ [kWh/wash]$

$E = Mean\ electric\ energy\ consumption\ [kWh/wash]$

$W = Mean\ water\ use\ per\ wash\ [gal/wash]$

The PBL laundry washing machine exceeds the efficiency standards with a modified energy factor of $12.6\,ft^3/kWh/wash$ and a water factor of $2.5\,gal/ft^3/wash$.

Chapter 2: Monitoring Plan

Field Test Site

A fitness facility in Sacramento California was chosen to be the field test site. The fitness facility was opened in 1985; it includes multiple fitness and workout rooms, a pool, a sauna, a steam room, and numerous racquetball courts. The total floor space is 52,000 square feet.

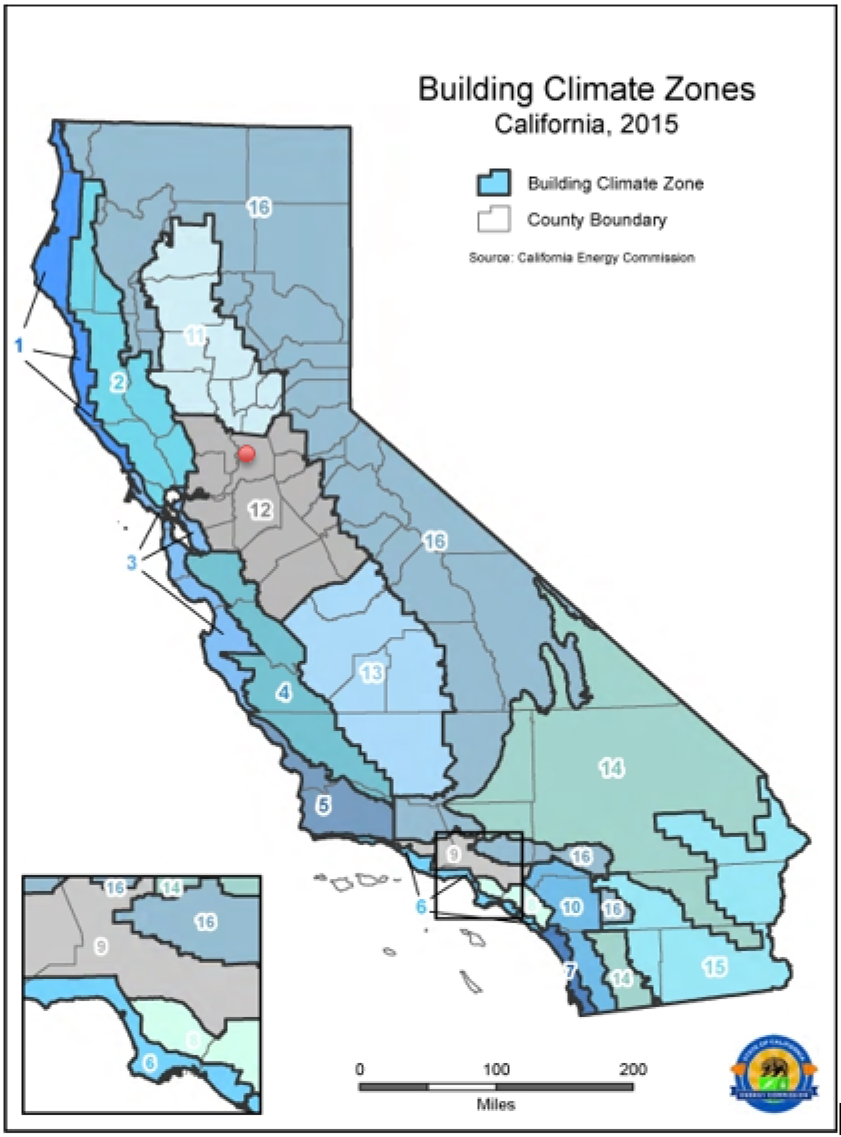


Figure 20: Site Selection for PBL Test, Shown in Red

The fitness facility cleans its laundry onsite, which consists primarily of towels used by patrons of the facility but also includes clothing and uniforms of the staff. The PBL laundry washing machine is especially suitable for cleaning towels since the towels do not have pockets or folds that can trap the polymer beads.

Tested Systems

The laundry washing machine chosen for use as a baseline system is a typical Industrial Washer Extractor. The specifications of the baseline and PBL systems used in the field study are shown in Table 1.

System Specifications		
Model	Baseline Industrial Washer Extractor	PBL Polymer Bead System
Capacity	60 pounds	65 Pounds
Weight	1230 Pounds	3968 Pounds
Motor Size	5 HP	10 HP
Height	65"	86"
Depth	53.8"	61"
Width	37.2"	52"
Warranty	5 year warranty on frame, 3 year limited warranty on parts (doesn't cover normal wear items)	Warranty included with lease

Table 6: System Specifications of the Baseline and PBL Washing Systems

Although both systems have similar load capacities, the PBL is much larger, has twice the size of motor and weighs over three times as much as the baseline system.

Instrumentation

Both the baseline and the PBL laundry washing machines were instrumented to provide continuous monitoring of their performance. Table 2 lists the instrumentation used to monitor the baseline laundry washing machine, and Table 3 lists the instrumentation used to monitor the PBL laundry washing machine.

Measurement	Manufacturer Model #	Accuracy	Installation
Power Consumption	Dent Powerscout 3+	±1% of reading	On main power Cord
Water Consumption	Omega FTB 4607	±1.5% of reading	On Supply Line
Hot Water Temperature	Omega RTD-NPT-72-E	± 0.17 °C	On Supply Line
Ambient Water Temperature	Omega RTD-NPT-72-E	± 0.17 °C	On Supply Line

Table 7: Baseline Laundry Washing Machine Instrumentation

Measurement	Manufacturer Model #	Accuracy	Installation
Power Consumption	Dent Powerscout 3+	±1% of reading	On main power Cord
Water Consumption	Omega FTB 4607	±1.5% of reading	On Supply Line
Ambient Water Temperature	Omega RTD-NPT-72-E	± 0.17 °C	On Supply Line

Table 8: PBL Washing Machine Instrumentation

The natural gas consumption of the baseline system was not monitored directly; instead the temperature difference between the hot and ambient water and the flow rate of hot water was used to estimate the natural gas consumption. Since the polymer bead technology allows the PBL laundry washing machine to operate with water at ambient temperature, there was no hot water consumption to monitor.

Data from the sensors was logged at one minute intervals from December 2013 until May 2015. At the end of each day the recorded data was transmitted through a cellular modem to a server for real time monitoring and processing.

Additional Data Collection

The measurements for the water retention and load size were taken by facility employees using an Ohaus model SD 35 scale which has a measurement accuracy of ±0.1 pound. The scale has a digital display and is capable of weighing up to 77 pounds at one time.

Chapter 3: Results

Load Size and Water Retention

Although the spin cycles of washing machines extracts the majority of the water used to wash a load of laundry, some water is still retained. Water retention directly affects the amount of energy and time that must be used to completely dry a load of washed laundry. The time and energy use associated with drying each load of laundry was not investigated; instead the water retention was monitored and recorded.

The mean weight of a load of laundry washed in the PBL laundry washing system was 59.6 pounds. The water retained within a post-wash load of laundry in the PBL system had a mean weight of 49.2 pounds. This translates to a mean water retention of 0.825 pounds of water per pound of laundry.

By comparison, the baseline system had a mean load weight of 41.8 pounds of laundry per wash, with a mean water retention of 38.6 pounds of water per load. This translates to a mean water retention of 0.923 pounds of water per pound of laundry.

Resource Consumption Analysis

Water Consumption

Each load of laundry washed in the PBL system required a mean volume of 38.4 gallons of ambient temperature water. Each load of laundry washed in the baseline system required a mean volume of 51.5 gallons of hot water and 13.4 gallons of ambient temperature water. Thus, the baseline system used a mean total volume of 64.9 gallons of water per load of laundry. When compared to the baseline system, the mean total water use of the PBL system was 26.5 gallons less per load of laundry.

The mean total volume of water required to wash a pound of laundry in the PBL system was 0.644 gallons. The mean total volume of water required to wash a pound of laundry in the baseline system was 1.55 gallons. The PBL system uses 41% of the volume of water that is used by the baseline system to wash the same weight of laundry.

Site Energy Consumption

Gas

Since the PBL does not use hot water, there is no need for gas. The baseline system used approximately 541 BTUs of natural gas per gallon of hot water, which is equivalent to 0.00541 therms per gallon of hot water.

Equation 3 shows how the natural gas consumption was estimated.

Equation 20

$$\dot{Q} = \frac{\dot{V}_{hot\ water} \cdot \rho_{water} \cdot c_{p_{water}} (T_{hot\ water} - T_{ambient\ water})}{\eta} \cdot 3600 s/hr$$

Where:

$\dot{Q} = Natural\ gas\ consumption\ [BTU/hr]$

$\dot{V}_{hot\ water} = Volume\ flow\ rate\ of\ hot\ water\ [gal/s]$

$\rho_{water} = Density\ of\ water: 8.34\ [lb/gal]$

$c_{p_{water}} = Specific\ heat\ of\ water: 1\ [BTU/lb \cdot {}^\circ F]$

$T_{hot\ water} = Hot\ water\ temperature\ [{}^\circ F]$

$T_{ambient\ water} = Ambient\ water\ temperature\ [{}^\circ F]$

$\eta = Hot\ water\ heater\ efficiency$

The efficiency of the hot water heater was assumed to be 80%. Based on the measured temperatures and flow rates of water, the baseline system was calculated to consume natural gas at a mean rate of 541 BTUs per gallon of hot water. Multiplying by the mean hot water consumption per load of laundry and dividing by the mean weight per load of laundry results in a mean natural gas consumption of 667 BTU per pound of laundry.

Electricity

The data collected at the host site shows that the mean electricity consumption of the PBL system was 1.2 kWh of electricity per load of laundry. Dividing by the mean weight per load of laundry results in 0.020 kWh of electricity per pound of laundry washed in the PBL system. The mean electricity consumption of the baseline system was 0.409 kWh of electricity per load of laundry. Dividing by the mean weight per load of laundry results in 0.010 kWh of electricity per pound of laundry washed in the baseline system.

Source Energy Consumption

Although the PBL system uses more site electricity than the baseline system it does not use any natural gas. To compare the energy consumption of each system, the electricity and natural gas was converted to source energy. According to the EPA [3] the source-site ratio for electricity is 3.14 and for natural gas it is 1.05. The PBL system was found to consume 0.063 kWh of source energy per pound of laundry washed. The baseline system was found to consume 0.234 kWh of source energy per pound of laundry washed. Thus, the PBL system uses approximately 27% of the source energy used by the baseline system to wash the equivalent amount of laundry.

Carbon Dioxide Emissions

Another important comparison that can be made between the two laundry washing systems is the CO_2 emissions based on their gas and electrical consumption. According to PG&E [4] 0.391 pounds of CO_2 is released into the atmosphere for each kWh of electricity used and 11.7 pounds of CO_2 is released into the atmosphere for every combusted therm of natural gas. Every 1,000 pounds of laundry washed in the PBL system results is an estimated 7.88 pounds of CO_2 released into the atmosphere. The baseline system is responsible for 81.88 pounds of CO_2 for every 1,000 pounds of laundry washed. The operation of the PBL system results in approximately 90% less CO_2 emissions than the baseline system to wash an equivalent weight of laundry.

The results of the comparison between the PBL system and the baseline system are shown in Figure 3.

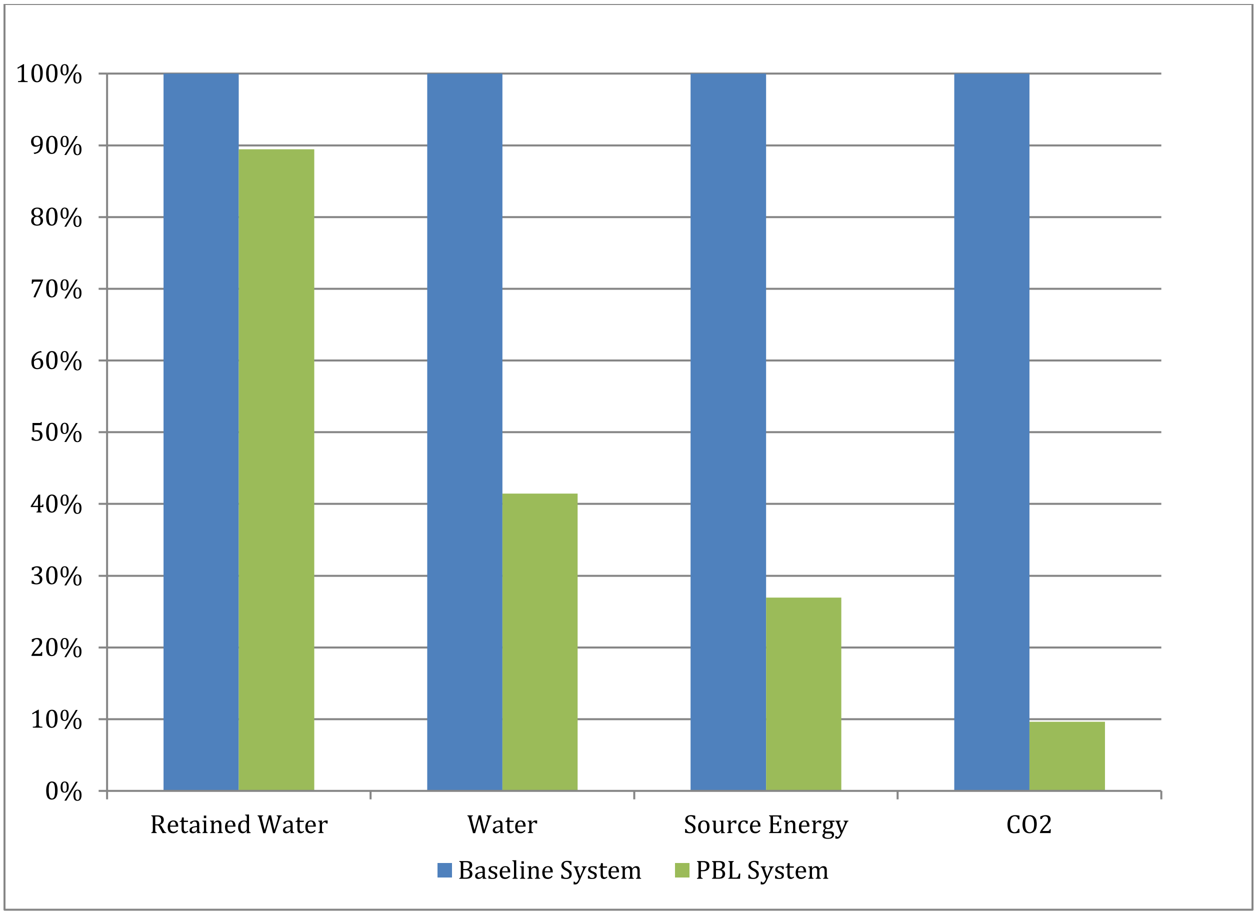


Figure 21: Resource Consumption of the PBL and Baseline Laundry Washing Systems

Life Cycle Cost Analysis

Materials

The materials that were accounted for in the cost analysis of the PBL and baseline systems were the laundry washing machines themselves and the chemicals that they used. It was estimated that the cost of a new baseline washer-extractor comparable to the one being tested is approximately $13,000. This cost was amortized at a rate of three percent for 12 years. This results in a fixed cost of $1,291 per year for the baseline system. The PBL system has a fixed yearly leasing cost of $11,700. With a deposit of $2,500 dollars on the $11,700 and a borrowing cost on the deposit of three percent, the total yearly fixed cost for the PBL system comes out to be $11,775.

The cost of chemicals for the PBL machine is included within the lease price. There are no additional costs for the PBL washing chemicals on top of the yearly fixed cost. According to data collected from the host site, the estimated yearly cost of chemicals for the baseline system is $2,736. The baseline system was used to wash 183,912 pounds of laundry over the course of one year. Thus, the cost in chemicals to wash 1,000 pounds of laundry is approximately $14.88.

Installation

The installation of both units was done by qualified professionals from their respective company. The installation of the PBL system cost $2,760 while the baseline system cost $3,590 to install. The cost of installation is not fixed and varies by locations and facilities setup. The cost of installation was not added to the cost analysis for the machines.

Resource Costs

Water

Based on data collected from the host site, the cost of fresh water and wastewater are $0.009963 and $0.009176 per cubic feet respectively. This comes to a total of $0.01914 per cubic feet of water used for washing laundry. This is equivalent to $2.55 per 1000 gallons of water. Based on the mean load weight and the mean water consumption per load of laundry, the cost of water is approximately $3.96 per 1,000 pounds of laundry washed in the baseline system and $1.64 per 1,000 pounds of laundry washed in the PBL system.

Gas

The cost of natural gas used in calculations was $1.12 per therm [6]. The PBL machine does not use any hot water and therefore does not use any gas. The baseline system was found to use 6.67 therms of natural gas per 1,000 pounds of laundry. Therefore, the total cost of gas for the baseline machine per 1000 pounds of laundry is $7.47.

Electricity

The cost for electricity used in calculations was $0.16 per kWh [7]. The field data shows that the PBL uses a mean of 20.1 kWh of electricity per 1,000 pounds of laundry. Therefore, the total cost of electricity per 1,000 pounds of laundry for the PBL machine is $3.20. The baseline machine uses a mean of 9.8 kWh of electricity per 1000 pounds of laundry and in turn the total cost of electricity per 1,000 pounds of laundry for the baseline is $1.56.

Maintenance

The lease on the PBL machine covers all maintenance costs associated with the laundry machine. The field data showed the yearly maintenance cost for the baseline system was approximately $350. The maintenance cost was calculated to be $1.90 per 1,000 pounds of laundry washed using the baseline system.

Total Cost

The costs can be summarized into total fixed and variable costs per machine. The only cost included within fixed costs was the cost of the machine. Therefore, the total fixed cost for the PBL machine was $11,775 per year and the total fixed cost of the baseline machine was $1,291 per year. The variable costs are those costs that are dependent on the amount of laundry washed by each system. For the PBL system the total variable cost per 1,000 pounds of laundry is $4.06 and for the baseline system it was $28.59.

The results of the cost analysis are summarized in Table 4 and the annual costs of each system are shown in Figure 4 as a function of the weight of laundry washed per day.

Table 9: Cost Analysis of the PBL and Baseline Systems

	Baseline System		PBL System	
		Fixed Costs		
Fixed Costs	Purchase Price	$13,000	Yearly Lease	$11,700
	Yearly Machine Amortized Cost (3% for 12 years)	$1,291	Deposit	$2,500
			Borrowing Costs on Deposit (3%)	$75
Total Yearly Fixed Costs		**$1,291**		**$11,775**
		Variable Costs		
Electical	Electricity / 1000 lb. (kWh)	9.8	Electricity / 1000 lb. (kWh)	20.1
	Electricity Cost ($ / kWh)	$0.16	Electricity Cost ($ / kWh)	$0.16
	Electricity Cost / 1000 lbs.	**$1.56**	**Electrical Cost / 1000 lbs.**	**$3.20**
Water + Sewage	Water Cost / 1000 gal	$2.55	Water Cost / 1000 gal	$2.55
	Water Used / lb Laundry (gal)	1.55	Water Used / lb Laundry (gal)	0.64
	Water Cost / 1000 lbs.	**$3.96**	**Water Cost / 1000 lbs.**	**$1.64**
Gas	Gas Cost ($ / Therm)	$1.12	Gas Cost ($ / Therm)	$1.12
	Hot Water (gal / 1000 lbs)	1233	N/A	
	Gas Use / 1000 lbs. (therm)	6.7		
	Gas Cost / 1000 lbs.	**$7.47**		
Chemical	**Chemical Cost / 1000 lbs.**	**$14.88**	**Included In Yearly Lease**	
Maintenance	Yealy Maintenance Cost	$350	**Included In Yearly Lease**	
	/ 1000 lbs	**$1.90**		
Total Variable Costs / 1000 lbs.		**$29.77**		**$4.84**
		Total Costs		
Total Yearly Fixed Costs		**$1,291**		**$11,775**
Usage	lbs / day	1000	lbs / day	1000
Total Variable Costs		**$10,865**		**$1,768**
Total Yearly Cost		**$12,157**		**$13,543**

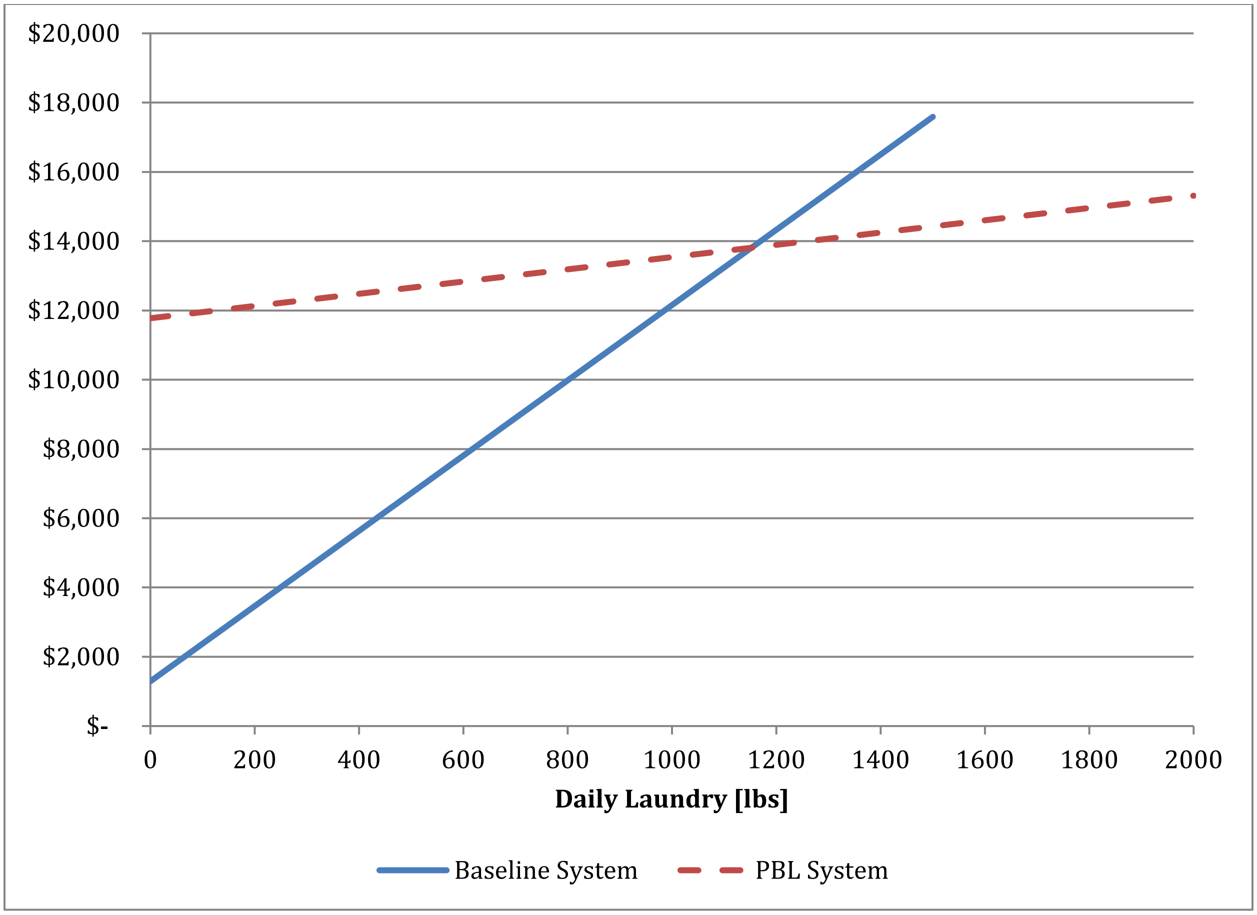


Figure 22: Annual Cost Comparison of the PBL and Baseline Laundry Washing Systems

If 1,000 pounds of laundry were washed per day, the total yearly variable cost for the PBL system would be $1,482 and for the baseline system it would be $10,434. The total cost per year, including both fixed and variable costs, for the PBL system would be $13,543 and for the baseline system it would be $12,156.

Chapter 4: Conclusions

The results show that the PBL system has significant potential to reduce resource consumption; however, the PBL is expensive compared to incumbent technology and this is likely to be a significant market barrier for the new technology. Although source energy was reduced by approximately 73% and water consumption was reduced by approximately 59%, the cost of these resources is low compared to the leasing cost of the PBL.

An estimated 1,100 pounds of laundry per day would have to be processed using the PBL system to have a similar total cost as a similar sized traditional laundry washing system. 1,100 pounds of laundry equates to an estimated 17 hours of non-stop operation per day. Many operations that produce enough laundry to benefit from the PBL will likely have washer-extractors, which can process up to 800 pounds of laundry per load. Additionally the large load machines cost significantly less than the PBL over a 10 year lifetime.

Future work should identify how to either expand the load size of the PBL or appeal to lower volume users by reducing the leasing price, while maintaining product quality. Future research should also consider the effects of reduced water retention, and the potential savings in dryer energy.

Chapter 5: REFERENCES

[1] Boarman William, 10 CFR Part 430, Subpart B, Appendix J1: Regulations Regarding Testing of a Clothes Washer, U.S. Government Publishing Office, 2011

[2] Boarman William, 10 CFR 431.156: Federal Efficiency Standards for Clothes Washers, U.S. Government Publishing Office, 2012

[3] Environmental Protection Agency, Energy Star Portfolio Manager Technical Reference Source Energy, July 2013

[4] PG and E, Greenhouse Gas Emission Factors, PG&E 2013

[5] Riesenberger James, John Koeller, Commercial Laundry Facilities, Koeller and Company, 2005

[6] U.S. Energy Information Administration, Natural Gas Prices, 2014

[7] U.S. Energy Information Administration, Average Price of Electricity to Ultimate Customers by End-Use Sector, 2014

APPENDIX G:
Post Assessment Final Report

EXECUTIVE SUMMARY

Introduction

The California Advanced Lighting Controls Training Program (CALCTP) is a statewide initiative with the goal of increasing the use of advanced lighting controls in commercial and industrial buildings to improve energy efficiency. Through proper installation, lighting controls improve energy efficiency, resulting in lower operating costs and a reduction in energy use. CALCTP trains and certifies licensed electrical contractors and state certified general electricians in the proper programming, testing, installation, commissioning and maintenance of advanced lighting control systems in commercial facilities.

Project Purpose

The goal of this task is to conduct post-assessment analyses of advanced lighting control system (ALCS) installations to verify the overall system performance. Analyses will compare the economic, energy and user acceptance impacts of projects installed by California Advanced Lighting Controls Training Program (CALCTP)-certified electricians versus projects installed by non-certified electricians.

Project Approach

The research team conducted four primary tasks: a literature review, data collection, data analysis and reporting. The literature review compiled existing knowledge of Advanced Lighting Control Systems (ALCS) capabilities, energy savings, installation cost, user satisfaction and the role of proper ALCS installation in achieving maximum benefits to end users.

Literature review results were used to develop data collection and analysis methods for each key research question. Data collection and analysis were conducted to determine ALCS capabilities, energy savings, installation cost, and user satisfaction. The research team compared calculated energy savings and actual energy savings for all surveyed ALCS projects. Actual system energy use relies on measured energy use collected at the site. Calculated energy use for pre- and post-retrofit systems is derived using assumptions identified in the literature review. To evaluate the difference in energy use for CALCTP certified and non-CALCTP certified ALCS installations, appropriate statistical methods are used (e.g., ANOVA, t-tests).

Various stakeholders were surveyed to evaluate the impact that the CALCTP program has on installation cost factors, including energy use expenditures before installation, after installation and the installation labor rate. Various stakeholders were surveyed to evaluate the impact that CALCTP certification had on end user satisfaction including the number of repeat customers, ease of lighting use by customer and overall customer satisfaction. End users were surveyed directly after the ALCS installation and two years after the installation.

Project Results

Key economic findings of the project show that for non-CALCTP installed projects, the average labor cost rate compared to total costs was 53 percent; whereas, the average labor costs for CALCTP installed projects compared to total costs was 43 percent, or 10 percent lower. This data supports that it is less costly (e.g., installers take fewer hours) to utilize certified teams.

Key barriers to ALCS market penetration include missing or erroneous information about quality, payback and costs; dispersed decision-makers including owners, designers, installers, managers, and operators; business-as-usual inertia; rapidly changing energy codes; and the fast pace of lighting technology and design practice change.

Research conducted in this study has demonstrated that ALCS installations are not meeting their full savings potential and thus not giving commercial building owners the returns they should expect on investments. By improving and addressing limitations in the labor force conducting these installations, enhanced training can bring advanced lighting control system costs down, improve returns on investment, decrease pay back lengths, and expand the market for ALCS technologies.

To further evaluate the CALCTP program, a pilot initiative using a bigger sample size with a consistent building stock with ALCS installations by both CALCTP and non-CALCTP installers is recommended. Ideally, the pilot program that would contain at least 30 CALCTP and 30 non-CALCTP projects to be statistically significant. During this study, it is recommended that a research question to compare the effectiveness of the installations to targeted Title 24 savings be included.

It is recommended that maintenance training be added to the CALCTP contractor certification program. The majority of projects struggled with end user understanding and comfort with maintaining the ALCS. It is recommended CALCTP consider adding a maintenance element to its program both for business owners/operators and contractors on how to improve customers' comfort with the technology upon project completion.

CHAPTER 1: Introduction

The California Advanced Lighting Controls Training Program (CALCTP) is a statewide initiative with the goal of increasing the use of advanced lighting controls in commercial and industrial buildings to improve energy efficiency. Through proper installation, lighting controls improve energy efficiency, resulting in lower operating costs and a reduction in energy use. CALCTP trains and certifies licensed electrical contractors and state certified general electricians in the proper programming, testing, installation, commissioning and maintenance of advanced lighting control systems in commercial facilities.[1]

The goal of this task is to conduct post-assessment analyses of advanced lighting control system (ALCS) installations to verify the overall system performance. Analyses compares the economic, energy and user acceptance impacts of projects installed by CALCTP-certified electricians versus projects installed by non-certified electricians.

Key research questions used to guide the post-assessment evaluation are:

1. How accurate are calculated energy savings at approximating actual energy savings for CALCTP and non-CALCTP certified installations?
2. Do ALCS projects installed by CALCTP-certified installers save more energy than project installed by non-certified installers?
3. Do CALCTP-certified installers deliver installation service at a lower cost with improved customer satisfaction?
4. Do ALCS projects installed by CALCTP-certified have a higher user satisfaction over time than installations performed by non-CALCTP installers?

1 California Advanced Lighting Controls Training Program (CALCTP). https://www.calctp.org/

CHAPTER 2: Background

The California Advanced Lighting Controls Training Program (CALCTP) was established in 2008 in cooperation with the California Energy Commission (CEC), the University of California Davis-California Lighting Technology Center, the California Community College Chancellor's Office—Advanced Transportation Technology Energy Campuses, California Investor-Owned Utilities (e.g., Southern California Edison, Pacific Gas & Electric and San Diego Gas & Electric), Municipal Owned Utilities (e.g., Sacramento Municipal Utility District), the National Lighting Manufacturers Association, the International Brotherhood of Electrical Workers and the National Electrical Contractors Association. The purpose of CALCTP is to increase the number of California state-certified general electricians with the knowledge, skills and abilities necessary to design, install, test, commission and maintain ALCS in commercial facilities. There are 31 CALCTP training facilities across the state at 21 joint apprenticeship and training centers, seven California advanced transportation technology and energy community college campuses and three utility energy training centers.

The demand for advanced lighting control-certified general electricians in California is driven by a unique mix of energy and environmental policy issues. In 2005, California consumed more than 252 billion kilowatt hours (kWH) of electricity, making it the second largest electrical power consumer in the nation with 6.9% of the national load. Commercial buildings are the largest consumers of electrical power, accounting for more than 40% of electrical consumption in the state. Interior and exterior lighting accounts for 41% of commercial building electrical load, more than twice the energy used for cooling. Office building use accounts for 25% of statewide electricity demand.

In the face of growing concerns about global climate change, the State of California passed the California Global Warming Solutions Act in 2006, prompting a series of policy actions by the CEC and California Public Utility Commission mandating stronger energy efficiency standards across all segments of California's economy and increased investment by both the investor-owned utilities and municipal-owned utilities in programs to encourage and support energy efficiency programs. Given the large share of California energy usage devoted to commercial lighting, the implementation of advanced lighting controls provides one of the biggest opportunities to reduce the electricity use and limit production of greenhouse gases related to global climate change. However, these reductions are only possible if advanced lighting controls are installed correctly.

CHAPTER 3: Project Approach

To address the key research questions, the research team conducted four primary tasks: a literature review, data collection, data analysis and reporting. The literature review compiled existing knowledge of Advanced Lighting Control Systems (ALCS) capabilities, energy savings, installation cost, user satisfaction and the role of proper ALCS installation in achieving maximum benefits to end users.

Literature review results were used to develop data collection and analysis methods for each key research question. Data collection and analysis were conducted to determine ALCS capabilities, energy savings, installation cost, and user satisfaction. The research team compared calculated energy savings and actual energy savings for all surveyed ALCS projects. Actual system energy use relies on measured energy use collected at the site. Calculated energy use for pre- and post-retrofit systems is derived using assumptions identified in the literature review. To evaluate the difference in energy use for CALCTP certified and non-CALCTP certified ALCS installations, appropriate statistical methods are used (e.g., ANOVA, t-tests).

Various stakeholders were surveyed to evaluate the impact that the CALCTP program has on installation cost factors, including energy use expenditures before installation, after installation and the installation labor rate. Various stakeholders were surveyed to evaluate the impact that CALCTP certification had on end user satisfaction including the number of repeat customers, ease of lighting use by customer and overall customer satisfaction. End users were surveyed directly after the ALCS installation and two years after the installation.

Literature Review

The research team conducted a literature review to compile existing knowledge of Advanced Lighting Control Systems (ALCS) capabilities, energy savings, installation cost, user satisfaction and the role of proper ALCS installation in achieving maximum benefits to end users. A cross-section of published studies addressing the aforementioned topics were referenced and results were compiled in this report.

Literature review results were used to develop data collection and analysis methods for each key research question.

Energy Savings Determination Method

The research team compared calculated energy savings and actual energy savings for all surveyed ALCS projects. Actual system energy use relies on measured energy use collected at the site. Calculated energy use for pre- and post-retrofit systems is derived using assumptions identified in the literature review. Information collected during the literature review included collection of theoretical values for building operating characteristics:

- Building Hours of Operation
- Occupancy Rate by Building Space Type
- Lighting System Power Consumption – Full Output
- Lighting System Power Consumption – Reduced Output
    - Tuning, or high-end trim
    - During periods of vacancy, daylight contribution and scheduling

To compare pre- and post-retrofit energy use cases, the following equations are used:

Δ_{v1} = Calculated Pre-retrofit Use – Calculated Post-Retrofit System Use

Δ_{v2} = Calculated Pre-Retrofit Use – Actual Post-Retrofit System Use

To assess significant differences between the two calculation methods exist, an analysis-of-variance (ANOVA) statistical approach is used. Variance in savings can be attributed to variance in any of the assumptions made during the development of the calculated savings. Other sources of variance in ALCS projects include variance in one or more building operating characteristics, not related to improper installation or device commissioning. Variance attributed to improper installation and/or commissioning of ALCS devices include:

- Not energized/launched/programmed, zero savings
- Decommissioned, zero savings
- Improper placement, reduced savings
- Improper commissioning, reduced savings

ALCS Installation Evaluation Method

To evaluate the difference in energy use for CALCTP certified and non-CALCTP certified ALCS installations, appropriate statistical methods are used (e.g., ANOVA, t-tests). To learn if differences between installation teams and/or other factors contribute to greater energy use savings, collected site information is used to determine the correlation between energy use savings and control installation type and/or building type, described below:

- Installation type: Occupancy sensors, time clocks, energy management system, dimmers, wireless switches, workstation-specific control, preset scene control, photosensors, dimmable ballasts, dimmers and switches used to control group lighting, multilevel switching, manual dimming, and daylight harvesting.
- Building type: Business, factory, mercantile, storage, warehouse, restaurant, and education.

ALCS Installation Cost Survey Method

Various stakeholders were surveyed to evaluate the impact that the CALCTP program has on installation cost factors, including energy use expenditures before installation, after installation and the installation labor rate. Respondents had the option of completing a web-based or paper-based survey. Results were collated, cleaned, and analyzed using standard statistical software, techniques, and measures of significance. Means and frequencies are provided as appropriate across all factors of interest to the research questions.

ALCS End User Satisfaction Survey Method

Various stakeholders were surveyed to evaluate the impact that CALCTP certification had on end user satisfaction including the number of repeat customers, ease of lighting use by customer and overall customer satisfaction. Respondents had the option of completing a web-based or paper-based survey for both. Two surveys were deployed:

- Part I: Directly after ALCS installation (Appendix A)
- Part II: Two years after ALCS installation (Appendix B)

Site Selection

The study reviewed 19 projects. Nine were CALCTP projects and ten were non-CALCTP projects. Sites were selected based on the mix of technologies, mix of lighting manufacturers, and a mix of wired and wireless ALCS. Sites evaluated are provided in Table 1. Descriptions of the sites are provided in Appendix C.

Table 10: Evaluated Lighting Installation Sites

Non-CALCTP Projects	CALCTP Projects
Chet Holifield Federal Building	Office of the Future - Federal Building Demonstration
Cottage Way Federal Building	Office of the Future Landmark Square Pilot
Philip Burton Federal Building	Office of the Future Executive Suite Demonstration
Ron Dellums 8 - Federal Building	Commercial Tubular Daylighting System
Ron Dellums 13 - Federal Building	PG&E Emerging Technologies Program
Ron Dellums 14 - Federal Building	Veterans Administration Medical Center - San Diego
Roybal - Federal Building	San Mateo County Parking Garage
Environmental Security/Technology Certification Program - Building 279	Pleasanton Public Library
Environmental Security/Technology Certification Program - Building 602	CSU Fullerton's Titan Gym
Environmental Security/Technology Certification Program - Building 988	

CHAPTER 4: Project Outcomes

The research team conducted four primary tasks: a literature review, data collection, data analysis and reporting. The literature review compiled existing knowledge of Advanced Lighting Control Systems (ALCS) capabilities, energy savings, installation cost, user satisfaction and the role of proper ALCS installation in achieving maximum benefits to end users.

Literature review results were used to develop data collection and analysis methods for each key research question. Data collection and analysis were conducted to determine ALCS capabilities, energy savings, installation cost, and user satisfaction.

Literature Review

The research team compiled existing knowledge of ALCS capabilities, energy savings, installation cost, user satisfaction and the role of proper ALCS installation in achieving maximum benefits to end users from existing, publically available literature. Advanced lighting control systems offer benefit to utilities, commercial customers and building occupants. These benefits include:

- Energy savings
- Creating flexible lighting schedules
- Ability to track energy costs and savings in real time
- Ability to plan maintenance of lighting
- Ability to control lighting onsite or remotely
- Incorporating automated demand response capability into the system[2]

ALCS benefit the broader U.S. economy by generating economic activity and jobs. Green building investments, of which lighting controls are playing an increasing role, were projected to contribute $554 billion to the U.S. gross domestic product from 2009-2013 and 7.9 million jobs through 2013. Green building construction yields an annual output of $4.6 trillion and employs 120 million people.[3]

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2 Sacramento Municipal Utility District. SMUD Web Page. *Advanced Lighting Controls Program.* n.d. 2013.

3 U.S. Green Building Council n.d. USCBC Web Page. 2013.

Expected Energy Savings

The literature review revealed several positive statistics related to expected energy savings in commercial buildings. ALCS can reduce energy consumption from lighting by 50 percent in existing buildings and 30 percent in new construction[4]. This translates to significant cost savings. Owners can achieve 50 percent to 75 percent energy savings on existing bills by switching to advanced lighting controls[5]. ALCS can reduce lighting energy use by 35 percent to 55 percent assuming that advanced high efficiency technologies have not already been deployed at the site[6].

An analysis of 240 energy savings estimates from 88 demonstrations produced best estimates of average lighting energy savings for four primary lighting control strategies. Results of this research, conducted by Lawrence Berkeley National Labortory, are provided in Table 2.

Table 11: Average Lighting Energy Savings for Typical Control Strategies [7]

Strategy	Definition	Examples	Average Savings
Occupancy	Lighting status changes automatically based on presence of people	Occupancy sensors, timeclocks, energy management system	24%
Personal Tuning	Occupant control of light levels	Dimmers, wireless switches, workstation-specific control, preset scene control	31%

4 DiLouie, Craig. *Lighting Control for Existing Buildings*. May 12, 2010.

5 Sacramento Municipal Utility District. SMUD Web Page. *Advanced Lighting Controls Program.* n.d. 2013.

6 Raezer and Wilson. 2010. Raezer, David, and Romahlo Wilson. *TECH Note: Lighting Controls offer a reasonable first step towards improving energy efficiency.* July 2010.

7 Williams, Alison; Atkinson, Barbara; Garbesi, Karina; and Rubinstein, Francis; Lawrence Berkeley National Laboratory. *A Meta-Analysis of Energy Savings from Lighting Controls in Commercial Buildings*. September 2011.

Daylight Harvesting	Lighting status changes automatically based on daylight levels	Photosensors	28%
Institutional Tuning	Light levels tuned to space needs by application, ballast tuning (reduction of ballast factor), task tuning, lumen maintenance, group controls	Dimmable ballasts, and dimmers and switches used to control group lighting	36%
Multiple Strategies	Any combination of the above		38%

The research team’s literature review compiled industry research studies to further detail how ALCS’ can save energy in private office, open office, and classroom environments. Overall, ALCS control strategies range in their ability to provide lighting energy savings with occupancy sensors and daylight harvesting offering the deeper energy savings for these sites. The findings are provided in Table 3.

Table 12: Lighting energy savings for Typical ALCS Control Strategies per Application [8]

8 Lighting Controls Association. 2013.

Application	Controls Strategy	Lighting Energy Savings	Reference
Private Office	Occupancy sensor	38%	*An Analysis of the Energy and Cost Savings Potential of Occupancy Sensors for Commercial Lighting Systems*, Lighting Research Center/EPA, August 2000.
	Multi-level switching	22%	*Lighting Controls Effectiveness Assessment*, ADM Associates for Heschong Mahone Group, May 2002.
	Manual dimming	6-9%	*Occupant Use of Manual Lighting Controls in Private Offices*, IESNA Paper #34, Lighting Research Center.
	Daylight harvesting (side lighting)	50% (manual blinds) to 70% (optimally used manual blinds or automatic shading system)	"Effect of interior design on the daylight availability in open plan offices", by Reinhart, CF, National Research Council of Canada, Internal Report NRCC-45374, 2002.

Open Office	Occupancy sensors	35%	National Research Council study on integrated lighting controls in open office, 2007.
	Multi-level switching	16%	*Lighting Controls Effectiveness Assessment*, ADM Associates for Heschong Mahone Group, May 2002.
	Daylight harvesting (side lighting)	40%	"Effect of interior design on the daylight availability in open plan offices", by Reinhart, CF, National Research Council of Canada, Internal Report NRCC-45374, 2002.
	Personal dimming control	11%	National Research Council study on integrated lighting controls in open office, 2007.
Classroom	Occupancy sensor	55%	*An Analysis of the Energy and Cost Savings Potential of Occupancy Sensors for Commercial Lighting Systems*, Lighting Research Center/EPA, August 2000.

	Multi-level switching	8%	*Lighting Controls Effectiveness Assessment*, ADM Associates for Heschong Mahone Group, May 2002.
	Daylight harvesting (side lighting)	50%	*Side lighting Photocontrols Field Study*, Heschong Mahone Group, 2003.

ALCS Installation Costs

ALCS installation costs are estimated between $1.00 and $2.50 per square foot. Assuming 55 percent energy savings and a cost of $1.00 per square foot, ALCS have a payback period of 2.7 years. Assuming 35 percent savings and a cost of $2.50 per square foot, ALCS have a payback of 10.7 years. This estimate assumes the use of five lighting control strategies: lumen maintenance, daylighting, task tuning, occupancy control, and scheduling.[9] Another estimate found a payback period of 1.4 to 5.8 years.[10] For buildings that already exhibit low energy use, payback times may be quite long with one study noting periods between 20 and 40 years. [11]

Specific installations are provided below for benchmarking future ALCS installations:

- **Toronto General Hospital** upgraded the lighting in its six-story 175,000-sq.ft. R. Fraser Elliot Building, which houses the hospital's executive offices, administration, research facilities, food service and emergency medical services. The project reduced lighting energy consumption by 74 percent and power demand by 37 percent. It generated annual cost savings of $0.45 per square foot. [12]

9 Raezer and Wilson. 2010. Raezer, David, and Romahlo Wilson. *TECH Note: Lighting Controls offer a reasonable first step towards improving energy efficiency.* July 2010.

10 Heschong Mahone Group, *Lighting Controls Effectiveness Assessment*, May 2002.

11 Wei, Joy; Enscoe, Abby; and Rubinstein, Francis; Lawrence Berkeley National Laboratory. *Responsive Lighting Solutions for the General Services Administration*. September 2012.

12 Mocherniak, Terry, and Howard Berger. *Advanced Lighting Control Is the Future of Lighting and Offers Building Owners and Managers a Great Opportunity to Save Money with Better Lighting.* March 2010.

- **General Services Administration Study of Federal Buildings** found that the sweet spot for savings was buildings/spaces that operated 14+ hours per day, utility rates above $0.10/kWh, and variable occupancy patterns. For the majority of sites in the study, lighting energy savings were approximately 30 percent as compared to the building's baseline conditions. This equivocates to an average energy use reduction of approximately 0.9 kWh per square foot per year. [13]
- **Veterans Administration Medical Center San Diego** integrated ACLS and realized energy savings of 50 percent. Twenty-nine percent of the reduction was from tuning and 21 percent of the reduction was from daylight harvesting. For this building, the cost to equip the office with ACLS was $5 per square foot, resulting in a payback of 6.2 years. [14]
- **ACE Hardware** outfitted a warehouse space with two different systems, a Metal Halide lighting system and an LED retrofit lighting system. Overall energy savings was 93 percent from a combination of LED lighting with combine control and fine zoning, with 50 percent of reductions from LED lighting and 43 percent from the control strategy.

Utility Incentives

Utilities and energy efficiency organizations have established that it is more cost-effective to reward customers for reducing demand than it is to expand energy supply through the construction of new power plants. Since the 1990s, utility and regional energy efficiency rebates have helped to drive demand for energy efficient lighting. In that time, $6 billion in rebates have been offered in 80 percent of the US. Advanced lighting controls are a growing piece of these efforts, with rebates for this technology tripling since 2009. Average rebates for different advanced lighting control technologies range from $20 to $46 for retrofitting, and $16 to $41 for new construction. [15]

ALCS User Experience

Measuring user satisfaction goes beyond energy, cost, and light level measurement to include brightness, light distribution, color, aesthetics, daylight, and ease of use for controls. The *Light Right Survey* (funded by the Lighting Controls Association, National

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13 Wei, Joy; Enscoe, Abby; and Rubinstein, Francis; Lawrence Berkeley National Laboratory. *Responsive Lighting Solutions for the General Services Administration*. September 2012.

14 Veterans Administration Medical Center San Diego. *Advanced Lighting Control System Assessment – Final Report*. December 15, 2010.

15 DiLouie, Craig. *Lighting Control Rebates Triple Since 2009.* April 16, 2012. Lighting Controls Association Website.

Electrical Manufacturers Association, General Services Administration and the Department of Energy) is a free tool for evaluating user satisfaction. [16]

In terms of daylighting, most occupants are unlikely to notice dimming of 20 percent in spaces with no daylight and 60 percent in spaces with substantial daylight. [17] A study of the Veterans Administration Medical Center in San Diego found through surveys that new lighting levels after the installation were preferred by occupants as compared to the previous lighting system, and that the energy manager was satisfied with the ease of the installation and level of control offered. [18]

A study of small office spaces found that occupants preferred low ambient lighting paired with task lighting, and exhibited statistically significant levels of perceived improvement after the implementation in terms of attractiveness, comfort, and visual quality. Compared to the old lighting system, 99 percent of those surveyed preferred the new system.[19]

A study surveyed occupants of an office with an ALCS lighting system, and found that occupants believed the ALCS controlled lighting system delivered better quality light with less glare. Satisfaction increased when the survey was conducted well after the installation. However, some users replied that the occupancy sensors turn off lights while they were in the space.

Occupants also said that they wanted to have more control over their lighting, which they had to go through a systems operator to have changed. This indicates that providing more space control to occupants can further improve end user satisfaction. Reiterating the findings of this study, another survey of occupants was found to be more satisfied with their new lighting system when the survey was given at a later date. When conducting a survey of occupants following a retrofitting project, it important to

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16 DiLouie, Craig. *Defining Lighting Quality Based on User Satisfaction.* September 10, 2012. Lighting Controls Association Website.

17 DiLouie, Craig. *Lighting Control for Existing Buildings.* May 12, 2010. Buildings Website.

18 Veterans Administration Medical Center San Diego. *Advanced Lighting Control System Assessment – Final Report*. December 15, 2010.

19 Heschong Mahone Group, *Lighting Controls Effectiveness Assessment*, May 2002.

allow users time to recover from inconveniences during the retrofitting project and to get some familiarity and experience with their new lighting system.[20]

Market Penetration Barriers

Key barriers to ALCS market penetration include missing or erroneous information about quality, payback and costs; dispersed decision-makers including owners, designers, installers, managers, and operators; business-as-usual inertia; rapidly changing energy codes; and the fast pace of lighting technology and design practice change.[21] Specific installation barriers for ALCS market penetration are listed below: [22]

- Lighting designers and contractors are often at odds regarding how lighting controls should be deployed, installed, and commissioned
- Contractors and installers do not always know how to properly commission the systems, and as a result they experience a high rate of call-backs and rework of installed systems
- Customers find that control systems do not operate as promised, and often remove or disable the systems in frustration

As architectural and lighting design is becoming increasingly proficient, the execution of the installation is increasingly the primary area in need of improvement. Best practices suggest that successful automated daylighting controls require a significant commissioning effort that includes calibration and functional testing in order to reach full energy-savings potential. One study found that median daylighting control systems were saving 23 percent of lighting energy, or 915 kWh saved for every kW of lighting controlled. The average effectiveness of these controls was only about 51 percent, meaning that inadequate installation lost almost half of the potential savings.[23]

Some observed problems in the installation and design process that can be improved through re-commissioning include: improper zoning; heavy internal shading; improper relay connection; defined light level targets; review of design documents for proper location, orientation, and sequence of components; functional testing of controls; owner training on proper use of controls; and furniture selection. A major factor in the success of ALCS projects "comes from contractors, commissioning agents and utility program

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20 Wei, Joy; Enscoe, Abby; and Rubinstein, Francis; Lawrence Berkeley National Laboratory. *Responsive Lighting Solutions for the General Services Administration*. September 2012.

21 Yancy, Richard. Webinar: *Green Light New York.* June, 20, 2012.

22 *CA Energy Efficiency Strategic Plan: Lighting Action Plan Best Practices.* 2010.

23 Energy Center of Wisconsin. *Commissioning for optimal savings from daylight controls.* 19 February, 2013.

implementers to demonstrate this value to building designers and owners and ensure that these steps are completed." [24]

ALCS vendors must carefully design the control zone plan in order to achieve full savings potential. The control zone plan describes which lighting loads are operated by which controllers and/or control strategies. Control zoning determines the functionality of the lighting control system, ensures the installation satisfies the owner's project requirements, and determines whether the installation is properly installed and performs as intended.[25]

Energy Savings

The research team compiled energy savings of installed ALCS systems in an effort to determine if the installation team impacts the energy savings. No direct link between the ALCS system energy savings and the installation quality can be conclusively drawn based on the data collected.

On average, the pre-retrofit lighting power density (LPD) for non-CALCTP installed projects was 0.9 Watts per square foot, as compared to CALCTP installed projects with an LPD of 1.31 Watts per square foot. After the installation of ALCS, the average LPD for non-CALCTP installed projects increased to 1.12 Watts per square foot, as compared to CALCTP installed projects which reduced the overall, average LPD to 0.85 Watts per square foot. Non-CALCTP installed projects increased their LPD in metered areas by 18 percent, while CALCTP projects decreased their LPD in metered areas by 35 percent. For CALCTP installed projects, all sites experienced a significant decrease in LPD ranging from 19 percent to 50 percent due to the installation of the new lighting system. For non-CALCTP sites, three sites experienced a decrease in LPD while the remaining sites experienced an increase in LPD ranging from two percent to 76 percent.

For pre-retrofit systems, the average measured energy use intensity (EUI) for non-CALCTP installed projects was an annual 2.79 kW per square foot, as compared to CALCTP installed projects whose average annual EUI was 5.29 kW per square foot. For post-retrofit systems, the average EUI for non-CALCTP installed projects decreased to an annual 1.80 kW per square foot, as compared to CALCTP installed projects whose average annual EUI decreased to 2.93 kW per square foot. For non-CALCTP installed projects, the annual EUI savings was 0.99 kW per square foot, or a savings of 30 percent.

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24 DiLouie, Craig. *Study Finds Commissioning of Daylight Harvesting Control Systems Critical to Success.* June 10, 2013. Lighting Controls Association Website.

25 DiLouie, Craig. *The Control Zone.* December 2012. Electrical Contractor Website.

CALCTP installed projects experienced an annual EUI average savings of 2.35 kW per square foot for a savings of 43 percent. For CALCTP installed sites, all sites experienced decreases in EUI ranging from eight percent to 67 percent. For non-CALCTP sites, all but one site had a range of annual EUI savings from four percent to 64 percent. Site specific LPD and EUI for pre- and post-retrofit lighting systems are provided in Table 4.

Table 13: LPD and EUI for Pre- and Post-Retrofit Lighting Systems

	Pre-Retrofit LPD in Metered Area	**Post-Retrofit LPD in Metered Area**	**Pre-Retrofit EUI**	**Post-retrofit EUI**
	(W/ft2)	(W/ft2)	(KWh/ft2/yr.)	(KWh/ft2/yr.)
Non-CALCTP Projects				
Chet Holifield FB	0.96	1.44	2.92	2.11
Cottage Way FB	1.03	0.92	2.52	1.32
Philip Burton FB	1.22	0.97	2.52	1.57
Ron Dellums 8-FB	0.68	1.2	2.75	2.01
Ron Dellums 13-FB	0.72	1.03	2.36	1.66
Ron Dellums 14-FB	0.67	1.17	2.72	1.64
Roybal FB	1.09	1.11	6.5	2.37
Environmental Security/Technology Certification Program				
Building 279	1.26	1.11	1.33	0.96
Building 602	1.14	1.17	1.81	1.74
Building 988	0.77	1.11	2.46	2.6
CALCTP Projects				
Office of the Future Federal Building Demonstration	1.51	0.87	5.29	2.33
Office of the Future Landmark Square Pilot	1.37	1.11	2.01	1.38
Office of the Future Executive Suite Demonstration	1.11	0.87	6.28	3.61
Commercial Tubular Daylighting System	1.4	1.1	3.09	1.01
PG&E Emerging Technologies Program	1.42	0.73	5.7	2
Veterans Administration Medical Center - San Diego	1.4	0.7	5.43	5
San Mateo County Parking Garage	1.1	0.85	1.18	0.8
Pleasanton Library	1.06	0.7	10.11	4.65
CSU Fullerton's Titan Gym	1.4	0.73	8.48	5.61

ALCS Installation Evaluation

The assumption exists that in an open bid process CALCTP-certified installers will bill at, or under, cost because they have the confidence in their technicians' ability to install lighting controls with minimal instruction and errors. To better understand if this assumption proved true in the surveyed projects, the research team compiled and compared the relative installation costs of each project.

For non-CALCTP installed projects, the average labor cost rate compared to total costs was 53 percent; whereas, the average labor costs for CALCTP installed projects compared to total costs was 43 percent, or 10 percent lower. Data supports that it is less costly (e.g., installers take fewer hours) to utilize certified teams. Project labor costs are provided in Table 5.

Table 14: Lighting System Labor Costs

Lighting Project	**Project Labor Cost (% of Total Cost)**
Non-CALCTP Projects	
Chet Holifield FB	52%
Cottage Way FB	55%
Philip Burton FB	57%
Ron Dellums 8-FB	49%
Ron Dellums 13-FB	51%
Ron Dellums 14-FB	54%
Roybal FB	52%
Environmental Security Technology Certification Program	-
Building 279	51%
Building 602	54%
Building 988	52%
CALCTP Projects	
Office of the Future Federal Building Demonstration	52%
Office of the Future Landmark Square Pilot	46%

Office of the Future Executive Suite Demonstration	48%
Commercial Tubular Daylighting System	39%
PG&E Emerging Technologies Program	41%
Veterans Administration Medical Center - San Diego	50%
San Mateo County Parking Garage	36%
Pleasanton Library	43%
CSU Fullerton's Titan Gym	36%

ALCS End User Satisfaction Evaluation

To understand if ALCS projects installed by CALCTP-certified teams have a higher initial user satisfaction as compared to satisfaction with installations performed by non-CALCTP installers, a survey was deployed immediately after the installation of the ALCS systems. The majority of participants, 14 of 16 participants, were satisfied with the lighting controls at the time of the post-installation survey. Comments from those who were not satisfied with the lighting controls cited flickering of the light sources, dimming limitations, and scheduling limitations. For both CALCTP and a non-CALCTP installed projects, the end users felt they needed additional support if an issue arose or long-term maintenance was needed.

Long Term End User Satisfaction Survey Results

To understand if ALCS projects installed by CALCTP-certified installers have a higher user satisfaction over time than installations performed by non-CALCTP installers, a survey was deployed three to five years after the installation of the ALCS systems. Of the original 16 surveyed projects, three projects were available to respond to this second phase of the end-user satisfaction evaluation survey. The three responsive projects were all installed by CALCTP-certified teams.

The end users were either satisfied or very satisfied with the work of the contractor. Training on how to operate the lighting controls system was provided by the installer, with all respondents being either satisfied or very satisfied with the training. When asked if the lighting controls were functioning as expected, one respondent replied yes while the other two responded ‘somewhat’ and ‘no’ respectively. For both respondents with underperforming systems, the underperformance was attributed to the original controls company being sold with no support offered for the installed software. When asked what the maintenance staff’s level of experience with lighting controls prior to the demonstration, two responded ‘somewhat experienced’ and one responded ‘very experienced.’

Respondents with underperforming systems reported that they had called the installation contractor or manufacturer about the lighting controls for maintenance or operation issues. For one site, the particular issue with the lighting controls equipment was to de-bug the controls. The resolution required re-commissioning of the product. For one site, the particular issue with the lighting controls equipment was to address that the product was ‘no longer supported’ and that the ‘system was failing’. The company that purchased the installed product was contacted for replacement controls.

The respondents were asked how satisfied the occupants of the building are with the lighting controls. Two respondents said ‘neutral’ and one was ‘dissatisfied’. When asked if they would recommend this lighting controls system to other facilities based on their experience, one respondent replied yes while the other two responded ‘no’ and ‘N/A’ respectively.

CHAPTER 5: Conclusions and Recommendations

Research conducted in this study has demonstrated that ALCS installations are not meeting their full savings potential and thus not giving commercial building owners the returns they should expect on investments. By improving and addressing limitations in the labor force conducting these installations, enhanced training can bring advanced lighting control system costs down, improve returns on investment, decrease pay back lengths, and expand the market for ALCS technologies.

To further evaluate the CALCTP program, a pilot initiative using a bigger sample size with a consistent building stock with ALCS installations by both CALCTP and non-CALCTP installers is recommended. Ideally, the pilot program that would contain at least 30 CALCTP and 30 non-CALCTP projects to be statistically significant. During this study, it is recommended that a research question to compare the effectiveness of the installations to targeted Title 24 savings be included.

It is recommended that maintenance training be added to the CALCTP contractor certification program. The majority of projects struggled with end user understanding and comfort with maintaining the ALCS. It is recommended CALCTP consider adding a maintenance element to its program both for business owners/operators and contractors on how to improve customers' comfort with the technology upon project completion.

APPENDIX A: Evaluation Survey, Part I

Site: ______________________________________

Contact Name: _____________________________ **Email:** ______________________

Purpose: The CALCTP R&E team is conducting a review of recent lighting controls installation projects to determine customer understanding and satisfaction with the products. Your support of this effort will greatly enhance our efforts.

Who installed the lighting controls?

How long ago were the lighting controls installed?

How long did the retrofit take?

On a scale of 1-5, (with 1 being worst and 5 being best), how satisfied were you with the work of the contractor?

Did the company provide you with an understanding of the lighting controls and how they worked?

Yes _______

No ________

On a scale of 1-5, (with 1 being worst and 5 being best), how satisfied were you with the system training provided by the contractor after the installation?

Have you called the installation contractor or manufacturer about the lighting controls?

Yes _______

No ________

If yes, how many times have you called back the lighting controls contractor or manufacturer?

If yes, on a scale of 1-5, (with 1 being worst and 5 being best), how satisfied were you with the response from the contractor?

What was the particular issue(s) with the lighting controls equipment?

Were the issues resolved in a timely manner?

Did the resolution require re-installation of the product?

Yes _____

No ______

On a scale of 1-5, (with 1 being worst and 5 being best), how satisfied are your occupants with the lighting controls?

What has been your maintenance staff's experience with the lighting controls prior to the Installation?

Advanced ______

Novice ______

None ______

On a scale of 1-5, (with 1 being worst and 5 being best), how satisfied are the maintenance staff with the lighting controls?

-

Please submit your survey results to: info@calctp.org.

If you have any questions regarding the survey, contact us at (877) 670-7910.

APPENDIX B: Evaluation Survey, Part II

Site: ______________________________________

Contact Name: _____________________________ **Email:** ______________________

Purpose: A review of lighting control installation projects is being conducted to determine customer understanding and satisfaction with the lighting control products. Your support of this effort will enhance the understanding of lighting control user acceptance. Please provide as much information as possible.

General

What is your age bracket? <25 25-34 35-44 45-54 55-65 66+

How important is lighting to you?

SCALE: -3 = Not Important at All / 0 = Indifferent / 3 = Incredibly Important

-3 -2 -1 0 1 2 3

Site Specific

What type of lighting end user are you at this site? (Circle one)

- Facility Manager
- Employee
- Visitor
- Maintenance Staff
- Other

What time are you typically in the space being evaluated?

Before 8 AM 8 AM to 10 AM 10 AM to Noon Noon to 2 PM 2 PM to 4 PM 4 PM to 6 PM 6 PM – 8 PM After 8 PM

To the best of your knowledge, who installed the lighting controls?

To the best of your knowledge, how long ago were the lighting controls installed?

To the best of your knowledge, how long did the retrofit take?

On a scale of 1-5, (with 1 being worst and 5 being best), how satisfied were you with the work of the contractor?

Did the company provide you with an understanding of the lighting controls and how they worked?

Yes _______

No ________

On a scale of 1-5, (with 1 being worst and 5 being best), how satisfied were you with the system training provided by the contractor after the installation?

Are the lighting controls currently functioning as expected?

Yes ____

No _____

If no, which part of the system is unsatisfactory in your opinion?

To the best of your knowledge, have any lighting controls been disabled or removed?

Yes___

No____

If yes, why? ____

Have you called the installation contractor or manufacturer about the lighting controls for maintenance or operation issues?

Yes _______

No ________

If yes, how many times have you called back the lighting controls contractor or manufacturer?

If yes, on a scale of 1-5, (with 1 being worst and 5 being best), how satisfied were you with the response from the contractor?

What was the particular issue(s) with the lighting controls equipment?

Were the issues resolved in a timely manner?

Did the resolution require replacement or re-commissioning of the product?

Yes _____ (Circle one): Replacement/Re-Commissioning

No ______

On a scale of 1-5, (with 1 being worst and 5 being best), how satisfied are your occupants with the lighting controls?

What has been your maintenance staff's experience with the lighting controls prior to the installation?

Advanced ______

Novice ______

None ______

On a scale of 1-5, (with 1 being worst and 5 being best), how satisfied is the maintenance staff with the lighting controls?

Based on your experience with lighting controls, would you recommend them to other facilities?

Do you have additional feedback regarding the lighting system installed at this building?

Please submit your survey results to: negraeber@ucdavis.edu.

If you have any questions regarding the survey, contact us at (530) 747-3847.

APPENDIX C: Site Descriptions

CALCTP Installed Sites

Office of the Future FB Demonstration

This project consisted of one half of the 12th floor of the Los Angeles FB (8,024 sq. ft.) occupied by a division of the Federal Bureau of Investigation. This building was previously de-lamped, retrofitted with T8 lamps and electronic ballasts and fitted with a relay-based lighting control system. The east half of the floor was relighted using state-of-the-art technology, while the west half was left in its original condition. Energy use metering before and after the relighting project allows for direct comparison of potential savings in a real workspace. Additionally, the new lighting system is capable of demand reduction, tuning and other energy-saving strategies.

A new lighting control system was installed. It comprises a central programming and processing server and a number of distributed control modules throughout the space, and can regulate on/off and dimming functions of lights. The system is based on generic 0 to 10 volt dimming ballasts, and is wired using conventional Ethernet cables (although it is not connected to the data system). In addition, a separate workstation motion sensor and plug strip was proved for task-light switching and switching of other loads not needed when the workstation was unoccupied.

The project was highly representative of the challenges and complications faced in retrofit projects in everyday office buildings. In this case, the design was limited by two problems common to older office buildings: encapsulated asbestos fireproofing and lack of seismic upgrading. To resolve these issues, the general lighting system was attached to the furniture, and more than 12,000 pounds of old light fixtures were removed from the ceiling to lessen seismic loads. A new ceiling using 90% reflective ceiling tiles was installed to increase lighting system efficiency. Finally, the connection to the emergency lighting system was simplified and improved.

Office of the Future Landmark Square Pilot

Southern California Edison (SCE), Brookfield Properties and the New Buildings Institute, in collaboration with the Lighting Design Alliance and Lutron Electronics, jointly conducted the Landmark Square Office of the Future (OTF) pilot project. This project demonstrates the efficiency and applicability of low ambient, highly controlled lighting systems in office spaces. The project was executed within the broader framework of the OTF Consortium, a group of utilities seeking to create a mechanism for incentivizing highly controlled and efficient office environments focusing on opportunities available in the tenant improvement process.

A summary of the installed lighting by space type indicates both a reflected ceiling plan and reflected floor plan. The specific controls implemented are described below:

- All fixtures are controlled by sweeps beginning at 10 p.m.
- All fixtures have dimming capability except the break room LEDs.
- Many fixtures are tuned to allow the max power as a percentage of the rated wattage. This is account for lamp lumen and fixture depreciation over time (e.g., 60% or 70%).
- Office use area specific controls and maximum tune settings include:
- Hallway: Occupancy dimming (70%/20%) – no wall controls
- Break room: Occupancy dimming (70%/20%) – no wall controls
- Private offices: Daylight dimming (60%/20%) and vacancy on/off control – wall control and occupant remote control
- Conference room: Occupancy on/off controls (70%/off) – GRAFIK Eye by Lutron scene selector and wall control
- Reception: Occupancy dimming (70%/50%) – wall control

Project partners renovated the lighting and lighting controls in a 1,577 sq. ft. office space in the 443,000 sq. ft. Landmark Square building in downtown Long Beach, California, and summarized the performance of the lighting design in accordance with the OTF Technical Guidelines. In addition, this report details the pre- and post-lighting systems and controls, compares the actual metered power and energy performance to the 2008 Title 24 code baseline, presents the code calculation basis and reveals some of the complexities associated with this approach.

Office of the Future Executive Suite Demonstration

In this project, the Executive Suites located in SCE headquarters were the main focus. Situated in a commercial office building, the site was owned and managed by SCE in Rosemead, Calif. The SCE executive offices occupied the fourth floor and provided an opportunity to measure energy use as well as to undertake a relighting project that met the architectural, aesthetic and functional demands of the space while employing current energy-efficient products and design techniques.

All spaces were equipped with digital lighting controls for all lighting with motion sensors, manual override, tuning and computer programmable control. The following summarizes the luminaire controls strategy:

- The entire lighting system is universally tuned down by 20%.
- All open office workstations were tuned to meet the preferences and needs of the occupant. Each workstation comes equipped with an occupancy sensor that turns on lights to the

occupant's preferred light level when someone arrives at the desk and reduces lighting levels to 15% power when the space is unoccupied.
- All private offices have motion sensors set to occupancy mode, which operates the lights with an auto-on when occupied and auto-off when vacant. Manual dimming is provided at a wall-mounted control unit.
- The conference reused an existing Lutron scene-selecting GRAFIK Eye System. This relies on the user to select the setting appropriate to the activity – video conference, meeting, etc.
- All public areas are on a time-clock schedule that turns off all art and decorative lighting after work hours and on weekends.

The executive office space consists of 14,635 sq. ft. and contains 20 occupants. The primary spaces comprise 10 private offices, an open office area and a video conference room. The building was built in 1984; the lighting system was last updated in 1999.

Commercial Tubular Daylighting System

In this project, ALCS was installed in a single-story warehouse office building used as the Southern California headquarters of the Trane Corporation. A lighting system was designed for this demonstration that reduces energy use and demand by using daylight and a multi-function lighting control system. The light fixtures dim according to available daylight and turn on/off based on occupancy. Lighting use was monitored to quantify the energy and demand savings. The project represents retrofit projects in typical single-story commercial office space.

A new lighting control system was installed, which includes the (1) Energy Controls system, using wireless signals to provide dimming control of the LED and fluorescent lamps; (2) dimming control, based on the amount of available daylight as measured by ceiling-mounted sensors in each room; and (3) occupancy sensors, to turn lighting fixtures on/off based on occupancy in the room.

This project consists of six individual offices, a common copy room and break room – built inside a warehouse style building with drop ceilings and a tall attic space. The roof has built-in skylights, but they only illuminate the attic space above the drop ceiling. The ceilings in the demonstration area are 10 feet tall. There are no wall switches for lighting in the demonstration area, only occupancy sensors. The demonstration area consists of 1,780 sq. ft.

Integrated Lighting System Product

This project used integrated lighting system products (ILSPs), which constitute a collection of lighting technologies "offered as an integrated functional package by a manufacturer." This study was implemented in open office buildings within the PG&E

service area. Lighting systems of increasing levels of cost and benefit were designed for a typical open office building. All selected systems provided at least a 25% energy savings over the 2008 Title 24 requirements. The building was a single story building from the 1990s, roughly 14,200 sq. ft. The lighting systems consisted of the standard T8 fluorescent, first generation electronic ballast, three-lamp parabolic troffer. The lighting controls were 93% manual on/off, 5.5% energy management systems and 1.5% no controls.

The following ILSP solutions were implemented:

CODE COMPLIANT (meets minimal requirements for Title 24 Compliance)

Base Case

- Three-lamp parabolic fluorescent troffer fixtures with first-generation T8 lamp and electronic ballast
- Twenty-eight watt T8 fluorescent task lighting
- Time switch to automate shut-off controls

RETROFIT SOLUTION (Title 24 not invoked)

Good

- Retrofit existing three-lamp parabolic fluorescent fixtures with two-lamp T8 28 watt direct/indirect “basket” recessed retrofit kits
- Place 28-watt T8 task light in each work station

RENOVATION SOLUTIONS (Title 24 invoked – 2008 Version)

Better

- Replace existing three-lamp parabolic fluorescent fixtures with new two-lamp 28-watt T8 direct/indirect recessed fluorescent fixtures
- Place one-lamp 28-watt T8 task light with integrated occupancy sensor in each work station

Better Wired

- Replace existing three-lamp parabolic fixtures with new two-lamp 28-watt T8 direct/indirect recessed fixtures
- Place one-lamp 28-watt T8 task light with integrated occupancy sensor to each work station
- Add wired lighting controls that allow for scheduling, task tuning 17, demand response capabilities and occupancy/daylight control

Best Wired

- Replace existing three-lamp parabolic fixtures with new two-lamp 28-watt T8 direct/indirect pendants with dimmable ballasts
- Place LED task lighting with integrated occupancy sensor to each work station
- Add daylight harvesting system
- Add wired lighting controls that add scheduling, task tuning, demand response capabilities and occupancy/daylight control

Best Wireless

- Replace existing three-lamp parabolic fixtures with new two-lamp 28-watt T8 direct/indirect pendants with dimmable ballasts
- Place LED task lighting with integrated occupancy sensor to each work station
- Add daylight harvesting system
- Add wireless lighting controls that add scheduling, task tuning, demand response capabilities and occupancy/daylight control

High-Efficiency Office

The Encon building is located at Davis, Calif. The second floor was the location for the low ambient/task lighting retrofit. The office spans a central open area that contains nine workstations and a copy room. Around the perimeter lie six private offices, a reception area and ancillary spaces. A continuous corridor runs between the core area and the perimeter spaces.

The existing lighting used a mixture of luminaire types, including recessed, suspended and cove lighting. These lighting techniques are typically used to produce a high level of visual quality to create an attractive architectural appearance. There were four main fixture types installed prior to the retrofit:

1. A continuous line of 2’ 17 W T8 fixtures in the cove formed by the change in level from the 9’ to the 10’ ceiling, around the edge of the open office. These fixtures had no reflectors, and, the light from them fell mainly around the edge of the ceiling.
2. Suspended direct/indirect fixtures, each 8’ long and containing four 4’ T8 lamps. Three of these fixtures provided most of the light for the open office area. These fixtures produced mainly uplight, with some direct light coming down through perforated diffusers.
3. 2’x2’ recessed fixtures with nine cell louvers. These fixtures had 2x32 W U-shaped T8 fluorescent tubes. These fixtures provided most of the light for the perimeter corridor, the copy room, the private offices and the ancillary spaces.
4. A 4’x2’ version of the same louvered fixtures used above the corridor. These fixtures used three 4’ 32 W T8 lamps and lit the private offices.

The low ambient lighting system installed as a part of the retrofit consisted of three main types of light fixtures:

1. A continuous line of 1’ LED fixtures from Color Kinetics. These fixtures provide the cove lighting. They draw only around half the wattage of the previous T8 lamps and provide

approximately as much light on the ceiling.

2. Suspended T5HO direct/indirect fixtures from Finelite. Three of these fixtures provide most of the ambient light for the open office. They are similar to the existing suspended fixtures, but have a lower wattage and produce less light. These fixtures also provide the ambient light for the private offices.
3. Surface-mounted T8 wall washers. These illuminate the wall around the perimeter of the open office space (and the rest of the corridor that circles the space).

Occupants of the private offices had individual control of their overhead lighting via wall-mounted dimmers, bi-level wall switches and occupancy sensors by the doorways. The overhead fixtures in the open office area and the corridor were also on bi-level switches. Daylighting controls were not installed.

The energy savings were calculated and then estimated using a detailed before-and-after study of light levels, lighting energy use, and occupancy, time-of-use of light fixtures and controls and occupant satisfaction. The energy use of all light fixtures in the space was individually logged over two three-week periods using light level loggers, circuit current loggers and logging occupancy sensors.

Veterans Administration Medical Center – San Diego

This CALCTP site was the Veterans Administration Medical Center located in La Jolla, Calif. the location was chosen based on its willingness to allow for the installation and assessment of emerging or state-of-the-art technologies and participation in SDG&E® energy-efficiency programs. The office area chosen for the evaluation of the ALCS measures approximately 3,040 sq. ft. in the engineering department. This area consists of a six-story building dominated by an open floor plan with cubicles. The office operates 251 days/year. The working lighting hours are 11.5 hours/day. The annual working lighting hours are 2,886 hours.

There were 52 fixtures in the study, 44 of which were 2' x 4' recessed, lensed troffers. The other eight fixtures were 2' x 2' recessed, lensed troffers. Eight of the fixtures served as emergency lighting and were part of the two circuits for all lighting in the area. Eight of the 44 2' x 4' fixtures in the study were in three private offices (four in one office and two in each of the others); the rest were in an open floor plan area of 2,640 sq. ft. with work station cubicles. The open floor plan area will be the focus of this report.

The site initially had a four-lamp ballast controlling three lamps in one fixture and one lamp in another fixture. All fixtures were retrofitted with addressable four-lamp ballast and appropriate sockets to enable dimming and daylight harvesting prior to the energy-efficiency testing.

The ALCS used in this project consisted of a microprocessor-based lighting control system providing a full-range dimming and individual addressability of incandescent, low-voltage, fluorescent, LED and high-intensity discharge lighting sources. The system combines simultaneous wired (Digital Addressable Lighting Interface [DALI]) and wireless (Zigbee) communication.

Pleasanton Public Library

The Pleasanton Public Library is a 30,300 sq. ft. single story building that serves just under a million visitors annually. Before the lighting retrofit, the library's 61 light fixtures were on an average of 13 hours per day, seven days per week. The cost to operate the lighting was about $46,000 per year. The lighting controls were limited to three main switches that controlled the majority of the building's lighting with no timers or automation. This lack of suitable lighting controls resulted in all the lights being switched on whenever the facility was occupied, regardless of the number of occupants or daylighting opportunities.

The project included both a lamp and ballast retrofit and the installation of an Adura wireless lighting controls system. The 32-watt, two-lamp linear fluorescent T8 fixtures with magnetic ballasts were replaced with high-efficiency 32-watt two-lamp linear fluorescent T8 lamps and dimmable electronic ballasts. The control system included light controllers for each fixture, wireless gateways, wireless wall switches, occupancy sensors, photocells and the web-based Adura Enterprise Application. Wireless light controllers were installed on the retrofitted T8 fixtures, as well as on existing T5HO fixtures and a few compact fluorescent light can fixtures. The photocells provide information to the control system, which varies the brightness (and energy usage) of nearby fixtures according to available daylight. Occupancy sensors were installed in both the library public areas and private staff areas to automatically dim or turn off when these areas are unoccupied. Last, wireless on/off and dimming control switches were installed at various locations throughout the library to also provide staff with the means to manually control lighting. The project installation was completed in about a month.

California State University Fullerton's Titan Gym

As part of a comprehensive plan to create campus-wide climate neutrality, the university undertook an upgrade to the lighting of its multi-use Titan Gym. The facility is 16,600 sq. ft. in size and has a maximum occupancy of 4,000 people. The gym is part of a larger 139,000 sq. ft., physical education/kinesiology complex. Prior to the retrofit, gym occupants used a single set of switches to control all lights, resulting in more lights being turned on than were needed for a given activity. With no timers or automation to turn the lights off again, the gym's 68 400-watt metal-halide light fixtures were on an average of almost 16 hours per day, seven days per week during the academic year. In addition, the aging metal-halide fixtures presented other problems such as cave lighting and harmonic distortion.

The project included both a lamp and ballast retrofit and the installation of a wireless lighting controls system. The project replaced the 68 400-watt nominal metal-halide fixtures with 68 four-lamp T5HO F54 216-watt XtraLight fixtures with Lutron EcoSystem H Series dimming ballasts. The contractor installed Lutron's Quantum Total Light Management system, consisting of light controllers for each fixture, local controls, wireless wall switches, wireless occupancy sensors and web-based quantum lighting management software. As part of the installation, the contractor mounted wireless light controllers on the retrofitted T5HO fixtures and put in wireless occupancy sensors in the gym to automatically dim or turn lights off when areas are unoccupied. The contractor also installed wireless on/off and dimming control switches at various locations throughout the gym to allow occupants to manually control the lighting. The project installation was completed in less than two weeks.

San Mateo County's County Center Parking Garage

The San Mateo County's County Center Parking Garage rises to six levels and contains more than 900,000 parking spaces and 312,150 sq. ft. of space. The county had two main objectives for their upgrade: (1) to improve the quality and color rendition of the lighting and (2) to have better control of lighting energy use while maintaining or improving safety in the garage. Prior to the upgrade, the parking garage used 297 150-watt high pressure sodium fixtures, each of which required 188 w to power the lamp and ballast. These existing lights were on 20 to 24 hours per day, seven days per week.

The retrofit included a bi-level linear fluorescent fixtures (44-73W) and ballast retrofit and the installation of the Adura wireless lighting control system (279 in garage, 42 on roof). The light controllers regulate the light output based on input from occupancy sensors or an astronomical time clock if the fixture is located in a daylight area. The installation was completed in one month, with an additional month required for controls programming and commissioning.

Non-CALCTP Installed Sites

Responsive Lighting Solutions

The technology evaluated in this study is characterized as "Responsive Lighting Solutions." Responsive Lighting Solutions technology represents a comprehensive lighting retrofit package that has the following characteristics:

- Workstation-specific (WS) luminaires (light fixtures centered over individual cubicles);
- Dimmable ballasts that allow WS luminaires to provide preferred light levels for individual occupants;

- Sensors that allow WS luminaires to be dimmed or turned off when an individual cubicle is vacant; and

- A Lighting Management Control System that coordinates sensor information and occupant input to control and monitor lighting output and energy use.

This study focused on institutional tuning and scheduling, personal control and occupancy sensing. The study was conducted in seven sites located in five federal buildings in California selected to capture a diverse group of agencies, occupancy patterns, work styles, site conditions and baseline conditions. The participating sites were the following:

1. **Chet Holifield FB**: Large, deep, open office plan with a few private offices; the building 46,500 sq. ft. in size and located on the second floor southeast quadrant.
2. **Cottage Way FB**: Open office plan with a few private offices; 21,000 sq. ft. in size and located on the second floor of the northeast building.
3. **Philip Burton FB**: Private offices; 23,550 sq. ft. in size and located on the 10th floor west half.
4. **Ron Dellums FB**: Open office plan with a few private offices; 18,500 sq. ft. in size and located on the eighth floor.
5. **Ron Dellums FB**: Open office plan with a few private offices; 15,000 sq. ft. in size and located on the 13th floor.
6. **Ron Dellums FB**: Open office plan with a few private offices; 8,000 sq. ft. in size and located on the 14th floor in the south tower, west half of the floor.
7. **Roybal FB**: Combination of open office plan and private offices; 25,500 sq. ft. in size and located on the 18th floor.

Key technical attributes of system components were as follows:

- **Lighting management system:** The lighting management system is a DALI-based control system that offers operators individual ballast control and records sensor information and estimated power levels based on ballast settings.
- **Digital dimmable ballasts:** Digital ballasts (DALI ballasts in this study) allow operators to set light levels for individual ballasts, while continuous dimming provides a wide range of available light levels.
- **WS luminaires with built-in occupancy sensors:** By aligning individual luminaires with individual cubicles, WS lighting enables granular control based on individual cubicle occupancy and light level control based on personal preferences.

Environmental Security Technology Certification Program

The principal objective of this study was to measure the benefits of deploying advanced lighting control technologies at a representative U.S. Army installation (Ft. Irwin). In order to accomplish this goal, key lighting control strategies including scheduling, personalized dimming, daylight harvesting, occupancy sensing and scene setting were implemented. System solutions were specifically tailored to suit the unique characteristics and operating conditions of the three respective target facilities:

1. **Hybrid ILDC** system demonstration occurred in a section of Building 279 covering about 1,782 sq. ft. The building is made up of eight offices – some private and some with two or three occupants – and one conference room.

The targeted rooms featured only manual on/off switches at the room level. Each room targeted for retrofit has large 8' by 5' windows facing southeast that provide abundant daylight. Most rooms had worn vertical blinds. Some rooms have a fraction of window obstructed due to window mounted air conditioning units. The building has a hard ceiling, which makes wireless technology a preferred option for retrofit.

The section of the building chosen for the demonstration had 45 fluorescent T8, 32W two-lamp fixtures. A total of 42 fixtures were attached end to end in pairs, with each pair driven by a single four-lamp fixed output electronic ballast. The remaining three fixtures were driven by two-lamp fixed output electronic ballasts. Physical inspection of the lamps revealed that only about 54 lamps were operational out of the 90 installed lamps, probably due to a lack of maintenance.

2. **OccuSwitch Wireless** system demonstration was carried out in Building 602, a fully occupied single story office building with hard ceiling, which makes wireless technology a preferred option for retrofit. The building has 14 private offices, a conference room, a library, a mechanical room, a break room, two restrooms and two utility areas with exterior access.

The study targeted 4,821 sq. ft. of the floor area (out of total 5,000 sq. ft.) for lighting upgrades covering the entire building except for exterior utility rooms. Of the targeted area studied, 4,375 sq. ft. are included in all energy analysis. A circuit including the exterior utility rooms, the bathroom and the break room was excluded from analysis due to extremely different pre-retrofit and post-retrofit use patterns in the exterior utility areas, which were not included in the retrofit.

The pre-retrofit lighting system consisted of 101 fluorescent T8 32W four-lamp fixtures, which were driven by fixed light output ballasts. A large number of lamps were intentionally removed from fixtures to save energy, causing distorted light distributions. Physical inspection revealed that only 201 lamps were installed and operational out of 404 potential lamps, bringing the installed LPD to 1.43 W/sq. ft. out of a possible 2.46 W/sq. ft. (based on bench top measurements). The power supply is 120 volts AC. The building had only manual on/off switches, covering almost the studies entire 4,821 sq.

ft.

3. **Dynalite** system demonstration was carried out in a portion of Building 988, the current command headquarters. It is a single story administrative building covering that had only manual on/off switches prior to retrofit. The building comprises a variety of room types such as private offices, open plan offices, conference rooms, a surveillance room, a theater, a storage room and a copy room. The building has a standard drop ceiling, making it appropriate for the Dynalite system, which requires physical cabling to network together the luminaires, sensors and controllers.

The research team selected approximately 7,177 sq. ft. out of the total building area of 22,000 sq. ft. The pre-retrofit lighting in the target area consists of 85 fluorescent T8 32W three-lamp fixtures and six T8 32W two-lamp fixtures driven by fixed output ballasts. Some areas of the building were de-lamped to conserve energy. Before the retrofit, only 237 lamps were installed out of 267 potential lamps. The open plan office area exhibited light levels well below the code requirements causing occupants to complain about the existing lighting conditions. The power supply was 277 volts AC.

Ace Hardware LED High-Bay Lighting and Controls Project

This study was conducted on a lighting retrofit project in a 4,800 sq. ft. space within an Ace Hardware Distribution Center in Rocklin, California. The space is used as the aerosol storage room, and contains inflammable and aerosol products that the company sells in its stores.

There were 102 existing 400-watt metal-halide high bay luminaires mounted near the 25’ ceiling. The luminaire connected load was approximately 460 watt each, including ballast losses for magnetic ballasts. The existing lighting system did not have local controls. The lighting in the space was controlled via the breakers at the panel, which are at least 250’ away from the space with no direct line of sight to the lighting in the space. There are fourteen (14) 4’x8’ skylights, which provide a limited amount of daylighting in the space. No occupancy or daylighting controls were present in the baseline space. The existing high bay metal-halide luminaires were replaced initially with LED luminaires and then with the addition of lighting controls to the replacement LED luminaires.

This project evaluated the installation of an all-in-one retrofit lighting solution, employing LED light source technology, on-board occupancy sensors, daylight sensors and wireless communication combined to coordinate the activity, establish a control schedule and enable status monitoring.

The study comprised six control phases tested sequentially. Specific controls strategies were programmed into the controls system for each test segment. The six control strategies were:

1. **Post-Retrofit Strategy #1: LED Luminaires at 100%**

This strategy employed the same lighting controls approach that was being used for the pre-retrofit lighting system. The lighting was operated without integrated controls, and the light level was established at 100% of the luminaire output (full-on) for this test segment.

2. **Post-Retrofit Strategy #2: LED Luminaires at 70%**

The second post-retrofit baseline segment was collected after the lighting system was adjusted to reduce the light level to 17 foot candle (fc) average in the aisles, which is slightly higher than the target illuminance of 15 fc. All the additional controls operated at the top lighting level established at this 70% value.

3. **Post-Retrofit Strategy #3: Occupancy Control Only, Coarse Zoning**

This strategy employed the occupancy sensors as the only control device. The lighting was grouped into zones (one zone per aisle, and a zone for each cross-aisle or open area in the space), with a short delay time of 30 seconds. The lights dimmed to approximately 10% of full output for unoccupied periods during the workday.

4. **Post-Retrofit Strategy #4: Daylighting Control Only, Individual Control**

In this approach, the regular schedule of operation for the facility was used to establish a long occupancy sensor delay time so that once the first occupancy event occurred in the morning, the lighting remained on until the end of the regular day. During the day, the only adjustment to the lights was the response to daylight availability.

5. **Post-Retrofit Strategy #5: Combined Control, Coarse Zoning**

This strategy employed both daylighting and occupancy controls in the space in an approach that is consistent with the typical warehouse lighting control system as currently designed for new construction in California.

6. **Post-Retrofit Strategy #6: Combined Control, Fine Zoning**

This strategy employed a fixture-level controls approach enabled by the built-in occupancy sensor and daylight sensor in each luminaire.